Office of High Energy Physics Accelerator R&D Task Force Report

Appendix 3

William Barletta,

Accelerator Education in America

Accelerator Education in America*

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January 10, 2012

Accelerators are essential to discoveries in fundamental physics, biology, and chemistry. Particle beam-based instruments in medicine, industry and national security form a multi-billion dollar per year industry. More than 55,000 peer-reviewed papers with accelerator as a keyword are available on the Web. Yet only a tiny fraction of U.S. universities offer any formal graduate program in accelerator science and its core technologies despite some efforts by national accelerator laboratories to expand that presence in major research universities. Several reasons can be cited: 1) The science and technology of particle beams and other non-neutral plasmas cuts across traditional academic disciplines. 2) Electrical engineering departments have evolved toward micro- and nano-technology and computing science. 3) Nuclear engineering departments have atrophied at many major universities. 4) With few exceptions, student interest at individual universities is not extensive enough to support a strong faculty line. 5) Funding agency support of university-based accelerator research infrastructure is insufficient to support the development of new faculty lines.

What universities are at the core of training in accelerator science in the United States? The determining characteristic of a healthy university program is the presence of viable faculty lines with a minimum of two tenure-track faculty combined with regular core offerings. The field becomes slightly broader if one includes those physics and engineering faculties that have individual members with specialized interests in the field such as plasma-based accelerators. In addition some departments have nuclear and particle physics faculty who successfully place their students in national laboratories to do thesis research in accelerator physics and technology.

Group I, the major research universities in the United States with structured programs including graduate and undergraduate courses that are producing PhD level physicists are the following (in alphabetical order):

Cornell University
Indiana University
Michigan State University
Stanford University
University of California at Los Angeles
University of Maryland (College Park)

Also initiating structured Ph.D. programs in accelerator science are

Massachusetts Institute of Technology,
Old Dominion University (in affiliation with Jefferson Lab), and

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* This report is a work in progress and will be part of a longer invited paper to be published in Reviews of Accelerator Science and Technology.

[1] For a history of the USPAS sessions, see http://uspas.fnal.gov/

Stony Brook University (in affiliation with Brookhaven Lab).

To this list one may add Group II, universities with a single faculty member (either tenured or research faculty) whose primary research activity is accelerator science or multiple faculty with narrowly focused research activities:

Colorado State University
Duke University
Illinois Institute of Technology
Texas A&M
Northern Illinois University
University of California at Berkeley
University of Chicago
University of Hawaii
University of Southern California
University of Texas at Austin
Vanderbilt University

Some universities such as the University of Michigan and Columbia had produced some accelerator PhD's but now have none in the pipeline as the single faculty advisor has left or is no longer accepting students. A single interested faculty member has at best great difficulty sustaining a university program. An historical look[2] at the principal producers of PhD level accelerator scientists is given in figure 1. Rather surprisingly the number of students (MS and PhD) is a large fraction of (but in most cases is consistent with) the total historical production.

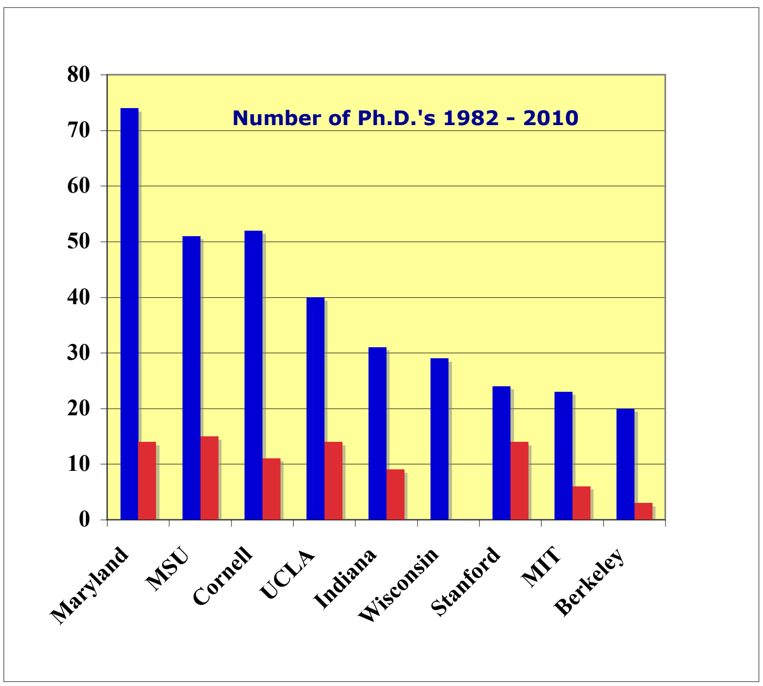


Figure 1: PhD's in accelerator science (blue) and present graduate students (red)

[2] Both sets of data have been provided to the author by the universities cited. Note that the expected number of PhDs produced annually is roughly 20% of the present level of students.

Even Group I universities offer only two or three regular courses in accelerator physics and technology. Some examples are given in the Appendix. The listed courses are generally an undergraduate and a graduate course in accelerator physics plus a regularly offered seminar style course in special topics. Therefore, all the universities in both Group I and Group II must rely heavily on the US Particle Accelerator School to provide the specialized academic coursework for their students. For this reason the USPAS rubric of for-credit courses hosted by major research universities is an essential aspect of formal accelerator education in America.

Students may register for one full course (≥ 45 contact hours) or choose two half-courses (≥23 contact hours each) where each half-course is one week in duration. By successfully completing the course requirements that include lectures, daily problem solving and examinations, students can earn university credit. A full-course earns the equivalent[3] of 3 semester hours of host university credit; each half-course earns the equivalent of 1.5 semester hours of credit. All courses run in parallel so students can take one full course, or two half-courses, or they may opt for only one half-course during either week of the program if the hosting university allows half credits. The percentage of students who take our classes for credit remains high, averaging 63%. In recent years the USPAS has had about 150 students (of all levels) per session.

The host universities generally require that course descriptions and instructor CVs be submitted roughly one year in advance of the session, to be vetted by their faculty. In addition, all USPAS courses are vetted and co-listed at Indiana University; Old Dominion is preparing to do the same. MIT students who take the undergraduate USPAS course receive MIT credit for course 8.277 and graduate students receive credit for 8.790.

Figure 2 combines USPAS attendance for the past decade with the data of Figure 1. Universities producing many PhDs make heavy use of the USPAS courses.

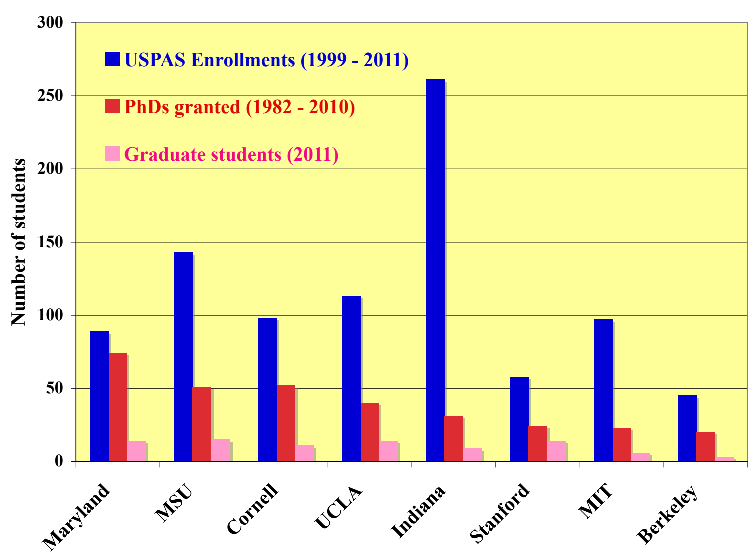


Figure 2: Student attendance at USPAS from the primary U.S. universities that produce PhDs in accelerator science

[3] Some of our hosts are on the quarter system; in that case an equivalent quarter credit is awarded.

USPAS offers a highly varied, responsive, and balanced curriculum of science, engineering, computational and hands-on courses. These offerings, distributed as shown in Figure 3 include:

Physics courses:

- General principles of accelerator physics, design of storage rings and synchrotrons, linacs, intense beam accelerators, beam optics, spin dynamics
- Synchrotron radiation sources, free electron lasers, strong field radiation,
- Beam theory, non-linear dynamics, collective effects, beam instabilities,
- Computational methods in beam dynamics, beam optics and electromagnetism,
- Radiation physics and accelerator safety, radiation effects,

Engineering and technology

- Experimental techniques, microwave measurement and beam instrumentation labs, accelerator vacuum labs, beam manipulation techniques
- RF systems, magnetic systems, superconducting magnets, superconducting RF, superconducting materials, beam sources
- Use of lasers in accelerators, optics-based diagnostics, optical-based timing systems
- High power electronics, pulsed-power electronics, high power rf-sources
- Shielding and accelerator safety systems,

Applications and management

- Accelerator applications in medicine, discovery science, and industry,
- Management of scientific research facilities
- Project management

Each year the USPAS offers one or more hands-on laboratory courses in which students learn to use sophisticated instrumentation such as network analyzers, fiber lasers, etc. Full, 2-week experimental courses in beam physics at operating accelerators are offered roughly every two years. The most recent of these offerings used the ERL-based free electron laser at Jefferson Lab. The next such hands-on offering will be at Duke in the Winter 2013. Unfortunately, due to practical considerations only a dozen students can be handled in such courses.

Whether at USPAS sessions or at universities, the lack of hands-on experience with running accelerators is a notable deficiency in the U.S. as compared with Europe, where there are several small accelerators at universities. This lack could be ameliorated with the development of optical-analog, beam-physics experiments[4] or small cyclotrons[5], including electron-model machines. The

[4] An optical analog pepper-pot emittance measurement experiment was developed for the S2009 USPAS course, "Accelerator and Beam Diagnostics" taught by Willem Blokland, Tom Shea and Alexander Zhukov, Oak Ridge National Lab; John Byrd, Lawrence Berkeley National Lab and Uli Raich, CERN http://uspas.fnal.gov/programs2/2009/UNM/courses/BeamDiagn.shtml

[5] A notable example is the 12-inch cyclotron plus instructional physics program built at Rutgers by Timothy Koeth and his student team. (http://www.physics.rutgers.edu/cyclotron/). This machine and program are briefly described in Appendix 2.

later could do cutting edge research in space charge dynamics at a machine cost of less than $500k while a student training model might cost less than one-half of that amount. Small synchrotrons using small, industry made magnets are also quite feasible and not all that expensive, but no one has looked seriously at them except Michigan State which built and operated a very small, four quadrant, electron synchrotron for studying beam physics at transition.

Typical class enrollment (see figure 3) ranges from 40 in our undergraduate class to several in highly specialized classes. This latter number explains why single universities cannot afford to offer specialty courses even if appropriate resident or guest faculty are available to teach.

As is common at most U.S. universities, at the completion of each course the students provide an evaluation of the course content selected by our faculty and of the quality of the instruction. These data provide feedback to the USPAS Director, Curriculum Advisory Committee, and USPAS Board of Governors as well as to the individual instructors.

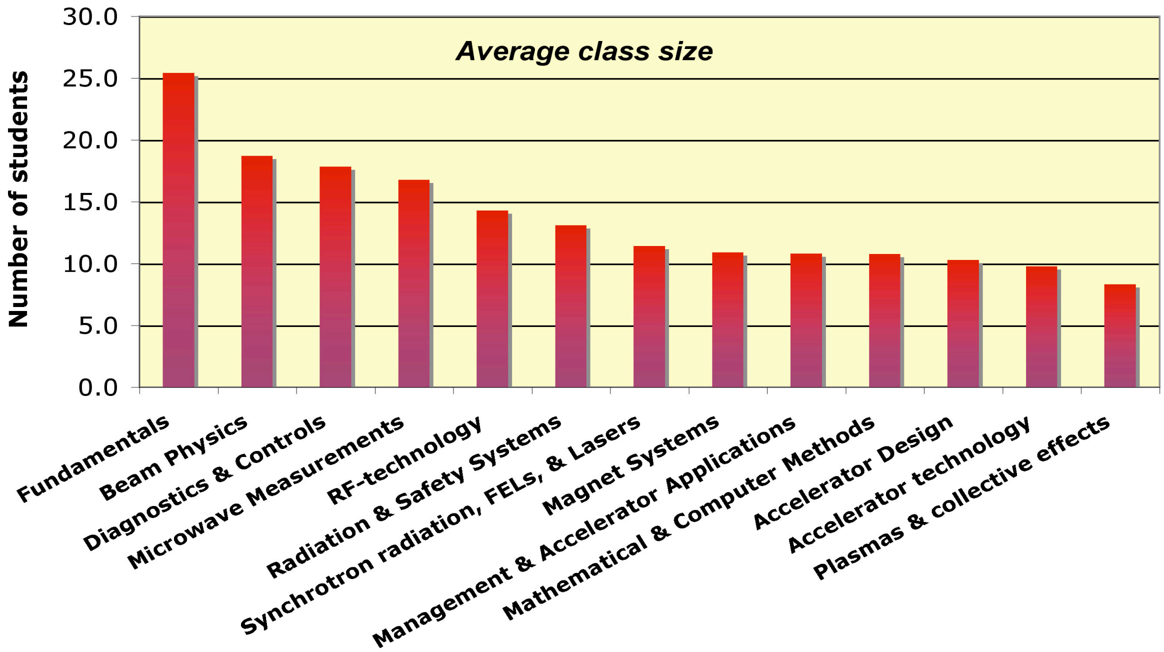


Figure 3: Average enrollment in USPAS courses by type

The USPAS also provides an unparalleled source of continuing education for accelerator physicists, technologists, and engineers from our national consortium members. Attendees from the national laboratories and partner universities remain our core constituency. Figure 4 shows the breakdown of attendees from our sponsoring institutions over the past twenty-four years. The institutions that historically have had largest accelerator operations (and operating budgets) send the largest numbers of participants. Normalizing MSU and Cornell by their respective operating budgets, one sees a participation level equivalent to Fermilab and SLAC.

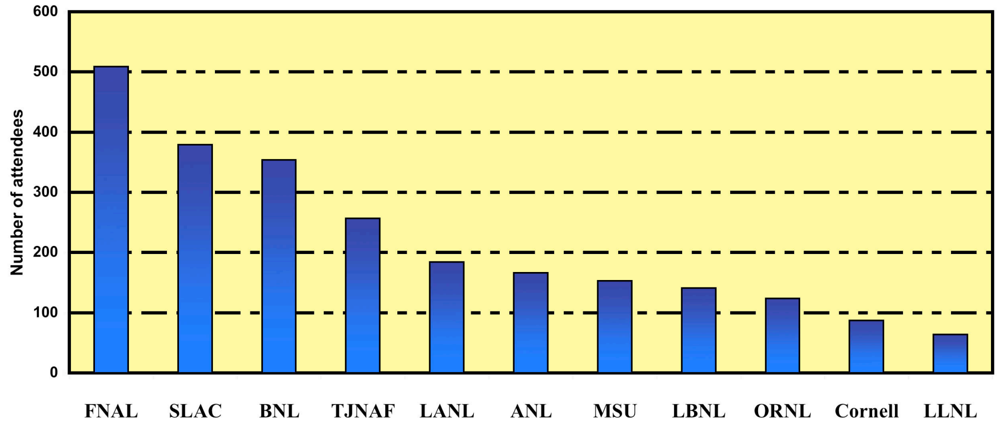


Figure 4. Attendance at USPAS sessions from sponsoring institutions from 1987 - 2011

With respect to overall interest in accelerator education from both degree-seeking students and those from the national laboratories and industry, the trend has been markedly upward in the past few years (Figure 5). Average attendance per session has risen less 130 to nearly 150.

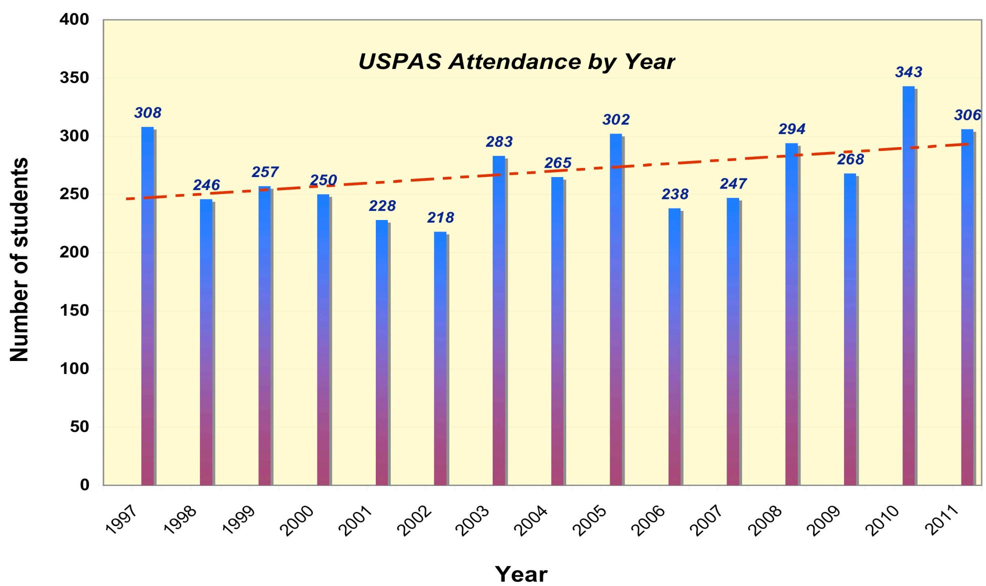


Figure 5. Student attendance at the past 28 sessions of the US Particle Accelerator School. The dashed line is a linear regression trend line.

The US Particle Accelerator School together with Indiana University offers the opportunity to earn a Master of Science Degree in Beam Physics and Technology. Students earn credit toward the Indiana University diploma at USPAS/university-sponsored courses by selecting their USPAS course for Indiana University credit instead of the host university credit. For each program, USPAS instructors are given visiting professor appointments and USPAS courses are added to the Indiana University curriculum. Award of a Master of Science Degree requires 30 hours of credit with a grade point average of B or above; a maximum of 8 credit hours may be transferred; some credits earned at previous USPAS courses may be eligible for transfer. There is a strict five-year limit to obtain the Master of Science degree. Generally, students may complete the Master's degree program within 3 years. At this time, we are unable to accept international students into the IU/USPAS Master's Degree Program. To date, IU/USPAS Master's Degrees have been awarded to seven students. Presently we have seven active students in the Master's program

A crucial part of any student's training is the opportunity to participate in cutting edge accelerator research programs. Given top-quality faculty supervision, students can do accelerator research in areas that are central to an institution's accelerator development program. An outstanding example of such work is the optimization of superconducting rf-cavity structures as part of Cornell's ERL research program. At MSU a large number of students play a strong active role in the NSCL program. NSCL graduate research topics include SRF cavity design, modeling, and measurement techniques, SRF-related material science, high-intensity ion-source development, large dynamic range beam instrumentation. At UCLA, the extensive, world-class experimental program in plasma accelerators, both in the Physics and Electrical Engineering Departments has produce a new generation of intellectual leaders in advanced acceleration techniques. At the University of Maryland, the novel electron-model storage ring (UMER) has played a vital role in advancing the understanding of the transport of space charge-dominated beams and has produced a substantial fraction of the PhD in accelerator physics and engineering from U.S. universities. DOE investment in a few more small research machines at universities would pay large dividends to the large accelerator-based science programs of the Office of Science.

It must be emphasized that many breakthroughs in accelerator science and technologies have been pioneered at universities with on-campus machines. A few examples are superconducting rf-accelerators (at Stanford and Cornell), superconducting compact cyclotrons (MSU), and pretzel orbits for high-luminosity collider operation (Cornell). Of course, such innovations require top-notch faculty lines[6] as well as highly talented students.

Of course increasing opportunities for PhD-level education will not be fruitful if talented undergraduates in physics and engineering are uniformed of and not attracted to them. As a first step to attract high quality students, the USPAS, Fermilab and Argonne National Laboratory instituted the Lee Teng Internships[7] in FY 2008. Teng Interns[8] should have just completed their junior year (or for exceptionally talented students, their sophomore year) prior to the summer of the internship. The interns take the USPAS course, "Fundamentals of Accelerator Physics," and then complete an eight-week research project at FNAL or ANL under the supervision of a mentor. The mentors remain available to guide the student through graduate school application

[6] When a university commits to a faculty line, it makes a commitment of a few million dollars. That means that universities must expect faculty in the hard science and engineering to be able to secure research grants of ~$300 to 500 k per year. Without sufficient opportunities from Office of Science program offices, one cannot expect a sufficient cadre of world-class accelerator faculty in US universities.

[7] http://www.illinoisacceleratorinstitute.org/

[8] Ten Lee Teng Interns are selected each year. The selection committee not only chooses the awardees but also matches them with the mentors at each laboratory. The author has been pleased to teach the Lee Teng interns each summer at the USPAS session.

and / or a senior thesis. Moreover, according to the Office of Workforce Development for Teachers and Scientists[9], participating in a summer research internship substantially raises the chances of a student's being selected for a DOE Office of Science Fellowship. The USPAS intends to propose to expand this program to the other Office of Science national laboratories plus four major research universities.[10] The cost for an expanded internship program would be approximately $300k per year.

The DOE national laboratories must and do play an essential active role in the education and training of accelerator scientists and engineers. Summer Undergraduate Laboratory Internships Student (SULI programs) are one way; providing instructors and financial support for USPAS session is another; providing research opportunities for thesis projects is a third.

Figure 6 shows an estimate of the average contribution that the consortium laboratories make from their own budgets each year to the annual USPAS educational program. This long-term funding commitment that the laboratories make to the annual USPAS budget is an exceedingly strong, public statement about the importance that they attach to the contributions of USPAS to the U.S. accelerator physics and engineering effort.

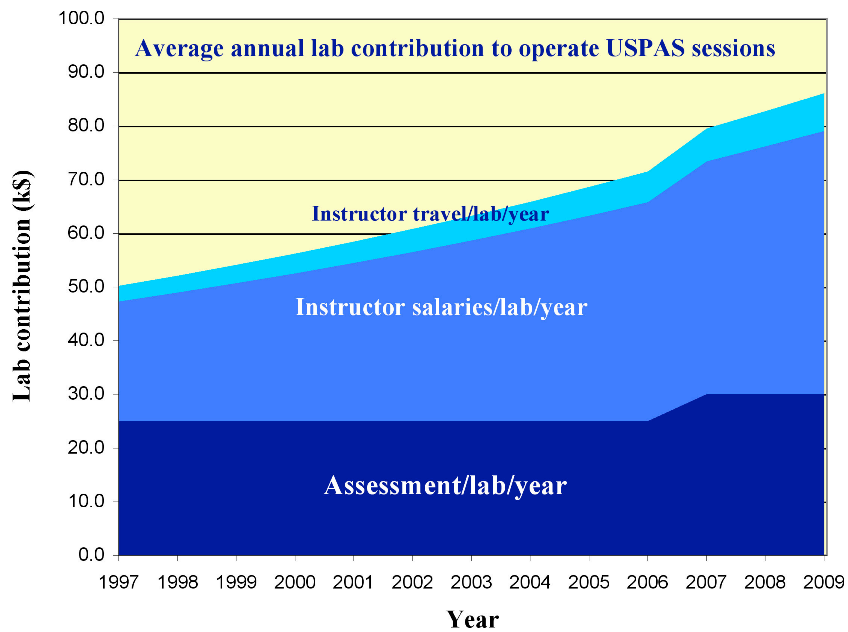


Figure 6. The monetized average annual contribution by Office of Science laboratories and USPAS consortium universities to operate the USPAS academic sessions.

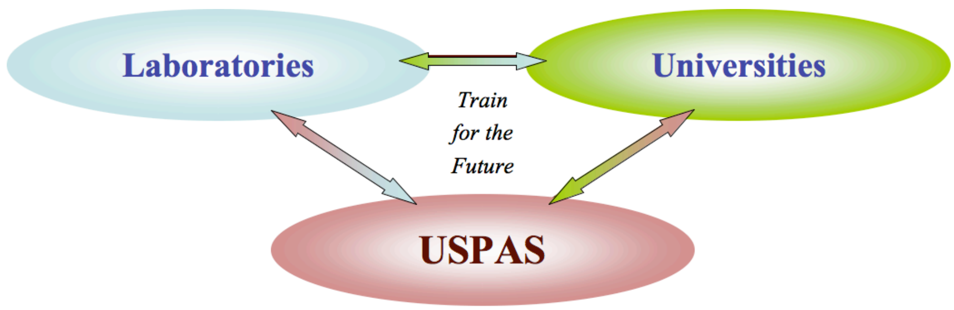
However, it would be a conceit to imagine that the laboratory system could supplant the principal role of major research universities with on-campus facilities. The Office of Science laboratories must attract top undergraduate talent to graduate study of accelerator physics and technology as well as to graduate study of accelerator-based science. A necessary condition is that

[9] Private communication, Dennis Kovar, 2010.

[10] An expanded internship program in industry or with the Department of Defense could be developed on a cost-sharing basis.

undergraduates must be made aware of the intellectual challenge and excitement of accelerators. However, the best undergraduates expect to study at a great research university. For the best graduate education, students should spend a large fraction of time on campus; an education at a great laboratory is not an education at a great university. Therefore the national laboratories must seek to enrich the intellectual life on campuses by creating new opportunities for significant accelerator research to be done on-campus.

Educating the next generation of scientists and engineers to build and pilot the engines of discovery for accelerator-based science, medicine, and industrial production must remain a strong three-way partnership. Each partner has an essential role that must be continually nurtured. The USPAS is proud of its role in the U.S. educational enterprise.



Summary recommendations

Over the past twenty-five years, U.S. education in accelerator science and technology has been carried out in a close, successful partnership among universities, national accelerator laboratories and the USPAS. Over that same period the accelerator-relevant infrastructure has atrophied considerably. Therefore, an important aspect of an accelerator stewardship program should be directed toward strengthening this partnership with the addition of more structured programs and hands-on training opportunities in research universities. Several universities have recently expressed new or renewed interest in developing advanced degree programs in accelerator physics, but new funding is going to have to be available from the DOE or NSF to support these new programs. At a few universities there is also interest expressed by electrical engineering and nuclear engineering departments. The latter are important for training students in areas such as high-power electronics or techniques of high-power thermal and radiation load design.

Judging from the attendance at USPAS sessions over the past five years, student interest has never been higher. Taking advantage of the opportunity these students represent will require an expanded investment in university-based accelerator research and in a new generation of hands-on training instruments. An accompanying expanded program of student internships would attract some of our most talented undergraduate physics and engineering students into graduate study in accelerator science and technology. The Unites States Particle Accelerator School has historically played a strong, central and institutionally neutral coordinating role in the education of accelerator physicists in the U.S. and looks forward to continuing that role as a vital part of the new stewardship program.

APPENDIX 1

Examples of Accelerator Science Courses in Accelerator Physics

Cornell courses
Undergraduate:

Physics 4456: Introduction to Accelerator Physics and Technology

Physics 4488: Advanced Topics in Accelerator Physics

Graduate:

Physics 7656: Introduction to Accelerator Physics and Technology

Physics 7688: Advanced Topics in Accelerator Physics

<u>Course Recommendations Beyond the Core Subjects : Strongly Recommended:</u>

PHYS 656 (7656) Introduction to Accelerator Physics and Technology
PHYS 657 (7657) The Storage Ring as a Source of Synchrotron Radiation
PHYS 688 (7688) Advanced Topics in Accelerator Technology

Cornell has always had a strong connection with the U.S. Particle Accelerator School (USPAS) and is a member of the USPAS consortium. Cornell faculty members have regularly been instructors for the USPAS since the accelerator school's inception. Cornell hosted USPAS sessions in 1988 and 2005.

MSU courses

PHY 861 -- Beam Physics

PHY 961 -- Non-Linear Beam Dynamics

PHY 962 -- Particle Accelerators

PHY 963 -- U.S. Particle Accelerator School

PHY 964 -- Seminar in Beam Physics Research

PHY 905 -- Special Problems (*recent offerings*)

RF Linear Accelerators, 2009

The Accelerator Physics of FRIB, 2011

MSU has provided distance-learning, on-line courses in beam physics through its VUBeam program for the past 20 years. A unique feature of VUBeam, which is jointly supported by OHEP and MSU, is that many, if not all, of the lectures are done live and fully interactive with the watching students communicating via some software originally developed by Cornell. MSU is an active member of USPAS consortium, and has offered several specialty courses in accelerator physics at NSCL in recent years. Most importantly, MSU has provided hands-on training to many accelerator physics graduate students who have made significant contributions in several areas.

MSU hosted the USPAS in 2007 and will repeat as host in 2012. By enrolling in PHY963, MSU students can enroll in USPAS course work and automatically earn graduate credit at MSU, regardless of where the USPAS course is held. One MSU faculty member has developed four separate courses for the USPAS and holds the record for the most courses and the number of student hours taught at the School.

MIT courses

Undergraduate

8.277 (6.608) Fundamentals of Accelerators, Lecture, three hours. Principles of charged-particle acceleration, principles of linacs, synchrotrons and storage rings, beam characterization, synchrotron light sources, medical accelerators, and free electron lasers.

MIT has hosted USPAS sessions in 1997 and 2010.

Stanford

Undergraduate

APPPHYS 324 Introduction to Accelerator Physics

Physics of particle beams in linear and circular accelerators. Transverse beam dynamics, acceleration, longitudinal beam dynamics, synchrotron radiation, free electron lasers, collective instabilities and nonlinear effects. Topics of current research in accelerator physics. Selected laboratory measurements at SLAC to augment the lecture material. Terms: alternate years, given next year | Units: 3 | Grading: Letter or Credit/No Credit

Stanford has hosted USPAS sessions in 1992 and 1998.

UCLA courses

Undergraduate

150. Physics of Charged-Particle and Laser Beams (4)

Lecture, three hours; discussion, one hour. Requisites: courses 1A, 1B, and 1C (or 1AH, 1BH, and 1CH), 110A, 110B, 115A, 115B. Physics of charged-particle and laser beams presented as a unified subject. Basic physics of charged-particle beams, covering relativistic particle motion in electromagnetic fields, transverse focusing, acceleration mechanisms, linear and circular accelerators, and advanced topics. Some fundamentals of laser physics, including gain and broadening mechanisms, linear light optics, laser resonators, and advanced topics and applications. P/NP or letter grading.

Graduate

250. Introduction to Acceleration of Charged Particles (4)

Lecture, three hours. Requisites: courses 210A, 210B, 215A. Principles of charged-particle acceleration, including principles of synchrotrons and storage rings, beam parameter determination, statistical behavior of beams and beam cooling techniques, synchrotron light sources, colliding beam storage rings, medical accelerators, and free electron lasers.

269C. Seminar: Accelerator Physics (2 to 4)

Seminar, three hours. Physics principles governing design and performance analysis of particle accelerators, using existing accelerators as examples and emphasizing interplay among design goals, component performance, and operational experience. S/U grading.

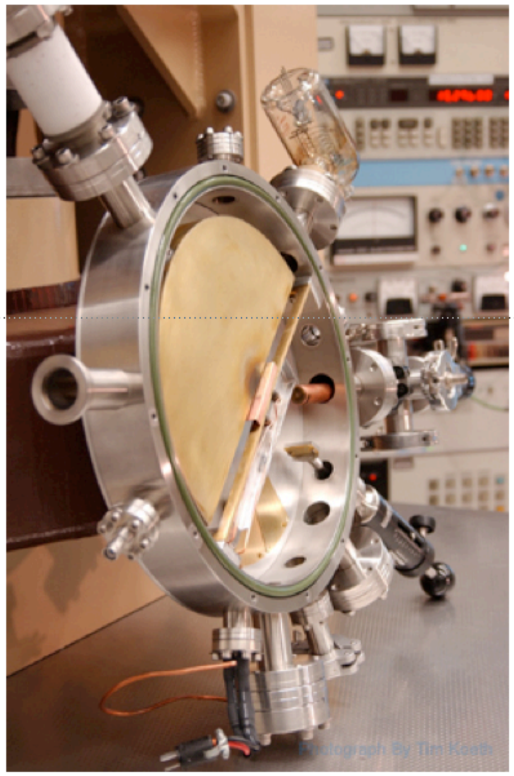
294. Research Tutorial: Accelerator Physics (2 to 4)

Lecture, one hour; discussion, two hours. Required of each graduate student doing research in this field. Seminar and discussion by faculty, postdoctoral fellows, and graduate students on topics of current interest in accelerator physics. May be repeated for credit. S/U grading.

UCLA has hosted USPAS sessions in 1994 and 2002.

APPENDIX 2

The 12-inch Rutgers Cyclotron is a research-grade accelerator capable of producing 1 million electron volt (1 MeV) protons that is used as a dedicated teaching tool employed in the Modern Physics Lab (MPL) courses at Rutgers University to give students a working introduction to accelerator physics.



It was designed and built by undergraduate students at a cost less than $100,000. Under the guidance of Dr. Timothy Koeth. The continuous evolution of this cyclotron, spanning more than a decade, is carried out by new generations of students, while project continuity is provided by dedicated volunteer faculty and staff. Because of the sophisticated level of the work, one or two students are chosen from the MPL class body and are committed to the cyclotron for an entire semester.

At the end of the semester, the cyclotron students compose one joint report as well as present their work to classmates in an oral session. Thanks to the labors of their predecessors, incoming students can now generate and manipulate beams under differing conditions, compare with simulations, and perform beam orbit analysis, all providing a comfortable introduction to the theory and practices of today's state-of-the-art accelerators. Because of their Rutgers Cyclotron experiences, five of the fourteen cyclotron students have altered their academic course to pursue accelerator science.

By their research with this machine the students have produced eight "white papers" of sophisticated experiments completed: Operation of a 9-Inch Cyclotron, Ion Source Studies: Parts I & II, 12-Inch Cyclotron DEE Voltage Studies, Observation of Betatron Motion, 12-Inch Cyclotron Magnet Studies, Electrostatic Deflector Energy Measurements, and Azimuthally Varying Field vs. Weak Focusing Pole Tips.

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Appendix 4
More university courses on accelerator-related fields

Editor's note: At the end of Appendix 3, Accelerator Education in America by William Barletta, is a list of university courses on topics in accelerator science. The courses listed below, not included in Barletta's list, are also university offerings on accelerator-related topics.

Colorado State

ECE/ENGR580 - Accelerator Engineering

Course description:

This course will introduce the student to particle beam accelerator technology and engineering - a multidisciplinary and broad field. A description of the historical development of accelerators and storage rings and the present uses of the various genres of machines will be provided. The basic principles and the important features of the action of electric and magnetic fields used in accelerators to bend, focus and accelerate charged particles will be presented. Special attention will be given to the technology, the design and the workings of accelerator components and peripherals systems including the magnets and the radio-frequency systems. The basic principles and the important features of the action of electric and magnetic fields used in accelerators to bend, focus and accelerate charged particles will be presented. Finally a glimpse into the accelerators of the future will be discussed. This course is suitable for third or fourth year undergraduate students and graduate students with a background in electrical engineering, physics, or applied physics.

ECE/ENGR581 - Microwave and Beam Instrumentation Lab

Course description:

This course will introduce the student to particle beam instrumentation, microwave measurements, and magnetic measurements used in the design and diagnosis of charged particle beam accelerator systems. Modern accelerators rely on beam manipulation, measurement and control using electromagnetic fields at microwave frequencies as well as through the use of magnetic fields to produce and control the beam in the desired manner. This course will consist of lectures introducing topics in beam instrumentation, microwave, and magnetic measurements that will then be performed in the laboratory environment by the students. This course is suitable for third or fourth year undergraduate students and graduate students with a background in electrical engineering, physics, or applied physics.

Colorado State is planned to host USPAS in summer 2013

Naval Postgraduate School

Graduate

PH4055 Free Electron Laser Physics

The physical principles describing free electron lasers are explained with applications to

ship defense from sea-skimming missiles, and to new radiation sources for scientific research. Theory is applied to experimental facilities around the world. Topics include optical resonator design, general laser concepts, laser beam propagation, relativistic electron dynamics, phase-space analysis, and
numerical simulation. Prerequisites: PH4353, E&M.

PH4056 Radiofrequency Weapons, High Power Microwaves, and Ultrawide Band Systems
The physical principles describing free electron lasers are explained with applications to ship defense from sea-skimming missiles, and to new radiation sources for scientific research. Theory is applied to experimental facilities around the world. Topics include optical resonator design, general laser concepts, laser beam propagation, relativistic electron dynamics, phase-space analysis, and
numerical simulation. Prerequisites: PH4353, E&M.

PH4353 Topics in Advanced Electricity and Magnetism (4-0) As Required
Topics selected from: Electromagnetic radiation, including radiation from antennas and accelerating particles, and radiation scattering from charged particles. Additional topics may include Cerenkov radiation, free electron lasers, and the relativistic formulation of electrodynamics. Prerequisites: PH3152, PH3352 and PH3991.

PH3360 Electromagnetic Wave Propagation (4-1) Summer/Winter
Introduction to vector fields and the physical basis of Maxwell's equations. Wave propagation in a vacuum, in dielectrics and conductors, and in the ionosphere. Reflection and refraction at the interface between media. Guided waves. Radiation from a dipole. Prerequisites: MA2121 and a course in basic electricity and magnetism.

University of Maryland

Graduate

ENEE 686. Charged Particle Dynamics, Electron and Ion Beams (3)
General principles of single-particle dynamics; mapping of the electric and magnetic fields; equation of motion and methods of solution; production and control of charge particle beams; electron optics; Liouville’s theorem; space charge effects in high current beams; design principles of special electron and ion beam devices.

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Appendix 5

Testimony of Jere Glover,
Executive Director of the Small Business Technology Council

Editor's note: The following is a brief summary taken from the testimony of Jere Glover, Executive Director of the Small Business Technology Council, at recent Congressional hearings on HR1540, showing the documented success of the SBIR program.

Small Business Technology Council of the National Small Business Association
1156 15th Street NW, Suite 1100, Washington, DC 20005

The SBIR Program – It Is Working!

The SBIR program is now 28 years old, with tens of thousands of awards and many studies. What are the conclusions? How is it being used by the SBIR agencies? Is it successful in the commercialization of advanced technology? Is it being copied anywhere else in the world? Is it relevant in today's economy?

· The most recent and most intensive study was a six-year analysis by the prestigious National Research Council of the National Academies published in 2008 by National Academies Press,[i] which concluded:

> "By strengthening the SBIR program, the Committee believes that the capacity of the United States to develop innovative solutions to government needs and promising products for the commercial market will be enhanced." (Paragraph 1.6, page 53)

· SBIR companies have produced approximately 25% of key innovations in the past 10 years– with only 2.5% of the Federal R&D extra-mural budget.[ii] The 11 agencies participating in the SBIR program have adapted the SBIR program to their particular missions with considerable success. (A Google search of "SBIR Success Stories" provides over 30,000 returns.) See SBIR Success Stories at www.sbtc.org.

· The commercialization success of the SBIR program is unparalleled in Federal R&D programs with its focus on the Phase III production outcome. According to the NAP study, "… approximately 30-40 percent of projects generate products that do reach the marketplace." (Page 129) This is further exemplified by the very high rate of patents generated by SBIR firms compared to universities and large businesses – 38% of U.S. patents for small business (with < 4% of the Federal R&D budget); 3% for universities (with 28% of the budget); and 55% for large businesses (with 36% of the budget).[iii] For universities, it is "publish or perish." For small businesses, it is "patent and produce products or perish." These commercialization efforts produce products, jobs and tax revenue to help pay for our universities.

· The NAP study also found that the following countries have adopted an SBIR-type program – Sweden, Russia, The United Kingdom, The Netherlands, Japan, Korea, Taiwan and other Asia countries (Page 54). A European Union policy paper has a goal of 15% of EU R&D funding to SMEs.[iv]

· Further, the NAP study found that the SBIR program builds meaningful bridges to universities:

> ". . . about a third of all NRC Phase II and Firm Survey respondents indicated that there had been involvement by university faculty, graduate students, and/or a university itself in developed technologies. (Page 64) . . . These data underscore the significant

> level of involvement by universities in the program and highlight the program's contribution to the transition of university research to the marketplace." (Page 65)

· SBTC believes that this partnership between universities and small business is an important economic multiplier that is unique to the U.S. innovation strategy. We have always strongly supported this partnership throughout the entire 28-year history of the program.[v] We see the important successes that these strong university/small business partnerships have created in Silicon Valley, Route 128, San Diego, Research Triangle Park, Ann Arbor, and others across the country. The U.S. needs more such programs.

· The importance of these partnerships is reinforced by the NAP study of 2002, wherein they state:

> "Public-private partnerships, involving cooperative research and development activities among industry, government laboratories, and universities, can play an instrumental role in accelerating the development of new technologies from idea to market."[vi]

· U.S. universities have produced 119 Nobel Laureates in the past 25 years, and they graduate the brilliant scientists and engineers that our innovative companies need. Small companies introduce the innovative products to the marketplace that keeps the U.S. in the forefront of technology. We need this partnership.

[i] *An Assessment of the Small Business Innovation Research Program*, National Research Council, National Academies Press; Charles W. Wessner, *Editor*, Committee on Capitalizing on Science, Technology, and Innovation; 2008; http://www.nap.edu/catalog.php?record_id=11989

[ii] *Where Do Innovations Come From? Transformations in the U.S. National Innovation System*, 1970-2006, published by THE INFORMATION TECHNOLOGY & INNOVATION FOUNDATION, Washington, DC July 2008.

[iii] *A New View of Government, University, and Industry Partnerships,* This paper was submitted by Jere Glover, Chief Counsel of the Office of Advocacy, at the Senate Committee on Small Business Roundtable Discussion on the SBIR program on August 4, 1999.

[iv] http://cordis.europa.eu/fp7/home_en.html

[v] *A New View of Government, University, and Industry Partnerships,* op. cit.

[vi] *Government-Industry Partnerships for the Development of New Technologies*, National Research Council, National Academies Press: Charles W. Wessner, Editor; 2002, page 23; http://www.nap.edu/catalog/10584.html

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Appendix 6

AES –
Examples of Lab and Industry Collaboration Funded by Government

Editor's note: The following is a copy of a statement from Alan Todd, Vice President, Advanced Energy Systems, Inc.

Recent UK government funding has facilitated the implementation of a unique accelerator test facility which can provide enabling infrastructures targeted for the development and testing of novel and compact accelerator technologies, specifically through partnership with industry and aimed at addressing applications for medicine, health, security, energy and industrial processing. The infrastructure provision on the Daresbury Science and Innovation Campus (DSIC) will permit research into areas of accelerator technologies which have the potential to revolutionise the cost, compactness and efficiency of such systems. The main element of the infrastructure will be a high performance and flexible electron beam injector facility, feeding customised state-of-the-art testing enclosures and associated support infrastructure. The facility operating parameters and implementation status will be described, along with primary areas of commercialised technology development opportunities.

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Appendix 7

Meyer Tool, Inc. –
Prioritizing the Advancement of Basic Science and Research

MEYER

January 31, 2012

Sandra Biedron
Colorado State University

Sandra:

Thanks for contacting me to provide input for your report to for the Department of Energy that in turn will go to Congress. Prioritizing the advancement of basic science and research, and maintaining the facilities to support this endeavor, is critical for America to stay at the forefront of innovation and early commercialization that will support our nation's long-term growth and prosperity. History has proven that future technological advancement in all the areas addressed in the study, while unknown in detail what is to come, definitely exists. America needs to identify avenues to speed the process while minimizing cost. This will promote opportunities for America to be "first to market" with the outcomes.

Being from industry, our suggestions and concerns stem from the marketability view and how to increase build-speed and minimize cost.

1. Enhance technology transfer initiatives. Look for ways to utilize lab/industry partnerships as early on in the process as possible to ultimately lower costs and increase speed of completion, therefore speed to market.
    a. Partner with industry from inception to garner input in every phase. We applaud the effort being made to include industry in developing a strategy.
    b. Allow best value industry to participate in Engineering Studies during the design phase. Partner with Industry fabrication specialists who can help scientists/physicists who know what they want/need the project to do, with people who have built similar or earlier generation designs. Fabrication specialists/shops can provide input on design build-ability. This can happen throughout the design process. For example, while determining the cost/benefit of various strategies, industry can be enlisted to provide practical industry knowledge of build costs. When a strategy is chosen, we can help streamline effective design before drawings are set in stone or to go out for competitive quote, enhancing the probability that the finished project will perform to expectations while lowering total cost and increasing speed to completion. When detailing designs that have never been built before, there are bound to be fabrication questions. Costly risks such as "extras" in the form of redesign or fabrication rework during the build phase are minimized through early industrial collaboration.
    c. When going out to competitive bid, request best value proposals, not lowest cost. Be sure that bids are awarded to industrial partners with the capability to execute in a timely fashion for lowest **total** cost, vs. initial low cost. Best value companies may offer best value strategies in their proposal. Best value suppliers are capable partners who mitigate cost

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through the life of the project. Initial low cost providers may lack the ability or capacity to perform obligations in a cost effective, timely manner. They may be unable to offer appropriate fabrication suggestions to the inevitable questions that arise during the life of the projects. All of the above can hinder a project timeline, adding dramatic cost including rework and increased cost of money. Develop criteria to evaluate suppliers so only those capable are considered for award and low-cost, yet technically weak suppliers are weeded out.

3. Address the skills gap/shortage in science/technology fields. Rebuilding U.S. manufacturing and the continued growth of high-technology industries are dependent on the availability of high-quality personnel, especially in the scientific and technical disciplines. The idea of U.S. laboratories partnering with educational institutions to use our research facilities as a training ground for next generation scientists and engineers, such as that suggested by the Illinois Accelerator Research Center (IARC) at Fermilab, is incredibly important for providing employable candidates with relevant experience and useful, next-generation skills that will be required to compete in the global market of the future. This will be of critical importance to support both a strong national industrial base and continuing research objectives which ultimately support economic growth and job creation. U.S. long-term ability to compete internationally depends on it.

4. Level the playing field for U.S. companies involved in U.S. taxpayer funded science projects. The U.S. allows foreign completion for these projects while European countries do not. In addition, European countries remove the effect of the Value Added Tax (VAT) levies (17-19%) for these bids, meaning that European companies are inadvertently favored in the U.S. bid process, reducing the effectiveness of "Buy American". Introduce policy to support American businesses as competitive partners. Eliminate the competitive advantage that the VAT tax reduction provides to European partners, resulting in a hindrance to American growth. U.S. industry does not have the same support internationally as we provide to our foreign competition when they bid on projects here at home. I've enclosed a summary of the VAT tax issue along with suggested action items for your reference.

5. Protect intellectual property. Do not trade American intellectual property to foreign competing governments for their "in-kind" contributions such as free labor. When the US or their national labs enter into these agreements, the result is trading a short-term advancement for our future. Other governments are willing to financially support these agreements because they are taking the long-term view. Gaining access to innovation and technological skills that they currently do not possess is the key to national competitiveness and future growth and prosperity. As the National Association of Manufacturers (NAM) states in their Technology Policy:

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MEYER

"Innovation is one of our greatest strengths and a major contributor to economic growth and industrial competitiveness. For this reason, it is important for policymakers both to nurture the creation and application of technology and vigorously protect intellectual property, as the creation of technology *is* the creation of intellectual property. Without strong protection, the incentives for future innovation-directed R&D will be inhibited.

The NAM supports a coordinated policy that strengthens the protection of intellectual property rights afforded by both domestic laws and international agreements and includes strong coordination and oversight by the governmental agencies tasked with protecting our nation's intellectual property. U.S. policy should reflect the vital importance of intellectual property rights for U.S. industrial competitiveness and made a priority item on the national agenda."

Please do not allow government labs to engage in agreements that trade our future away.

6. Initiate consistent and long-term funding policies that support a continued and competitive investment in basic science, research and long-term economic growth. Inconsistent year-to-year funding and/or national funding at levels inferior to our international peers, reduces our ability to achieve goals that will foster US ability to be "first to market" with innovation and technological advances.

Thank you for asking Meyer Tool & Mfg., Inc. to contribute. It is an honor and part of our personal mission.

Sincerely,

Eileen Cunningham
President

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Appendix 8

Niowave, Inc. –
DOE's Role in Commercialization of Particle Accelerators:
An Industry Perspective

DOE's Role in Commercialization of Particle Accelerators: An Industry Perspective

Terry Grimm and Jerry Hollister
Niowave, Inc.
Lansing MI
February 2012

The DOE's Office of Science has led the development of particle accelerators for basic research in the physical sciences. The advances made on accelerators at the DOE have opened a large array of high tech applications in defense, biomedical and industrial applications. Efficient transfer of this know-how to US industry has the potential to foster a robust high tech industry that dominates its international competitors [1].

The DOE laboratories' core mission is basic research, and from their founding days in the Manhattan Project have had a self-reliant culture that has tended to exclude industry involvement in research and development. Industry has been dealt with as a vendor and kept at "arm's length" to avoid the perception of a conflict of interest. In addition, the DOE labs have been operated as limited liability corporations that protect their intellectual property from industry and each other. Both of these policies limit tech transfer.

Because of the increasingly competitive international economy, we believe part of DOE's core mission should be the commercialization of their breakthroughs and know-how so that the US continues to prosper and lead the world. Therefore, we recommend that DOE pursue the following:

· **Private industry participate in DOE basic research and take a lead role when capable.**
This would likely increase DOE's budget to carry out the basic research, but lead to overall savings for the US government due to the value added to the US economy. Defense contractors are an example of partnerships between the government and industry where industry leads the R&D.

· **DOE participate in industrial research.**
DOE's contribution will add value to the US economy, and would compel industrial investment and effectively leverage the government's investment in basic research.

· **Intellectual property at the DOE laboratories should be freely distributed amongst other DOE laboratories and to US industry.**
This would reduce costs in the IP department of each DOE lab, and greatly enhance tech transfer and commercialization.

Finally, we believe the formation of DOE funded commercialization facilities at the DOE laboratories is unnecessary. Such commercialization facilities would be expensive to set up and operate, exacerbate the current "arm's length" culture, and add a layer of bureaucracy. Rather, we believe implementing our recommendations above will more efficiently develop strong public-private ventures that will lead the world in this important industry.

[1] Accelerators for America's Future, US DOE, June 2010, http://www.acceleratorsamerica.org/

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Appendix 9

Lawrence Berkeley National Laboratory – Ion Beam Technology

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

1) **Ion Sources and Injectors for Next Generation Accelerators**

Ion sources and injectors are critical components for the success of next generation accelerators for discovery science. Examples are the proposed Project X facility which will brake open the intensity frontier and a broad range of applications from spallation neutron source scaling (e. g. SNS upgrades), future transmutation of nuclear waste, accelerator driven reactors and fusion plasma heating (e. g. at ITER). Strategic investments into ion source and injector R&D can promises to deliver enabling technology with >10-fold improved performance in critical categories. Key ion source and injector requirements are:

- high brightness, i. e. high beam currents (pulsed and/or cw) and small emittance (<0.2 mm mrad) for negative hydrogen, protons and heavy ions
- high current for high power beams, e. g. multi-MW beams for fusion plasma heating by neutral beam injection, proton drivers for transmutation of nuclear waste, fusion fission hybrids, formation of secondary beams (muon, kaon, neutrino, …)
- ion source lifetime (i. e. the source operation time between service) and robustness
- efficient and reliable Low Energy Beam Transport (LEBT), including implementation of ion beam time structures on a ~10 ns time scale

Ion source development has an over 70 year old history. But recent advances in nanotechnology and advanced computing have not been folded into ion source design and operation concepts. With a commitment to focused R&D efforts, drastic enhancements in ion source performance could be achieved that could enable exciting science at the intensity frontier and advanced nuclear and fusion energy concepts and many spin-offs into industrial applications can be anticipated.

References:
- http://projectx.fnal.gov/
- http://www-ibt.lbl.gov/index.html (Ion Beam Technology group at LBNL)

2) Advanced accelerator technology for neutron and gamma generators

Neutron and gamma generators use nuclear reactions to generate useful yields of n- and γ-radiation. They are widely used for a broad range of applications of strategic importance in national security (e. g., active interrogation techniques for detection of nuclear material, nuclear non-proliferation and safeguards), industry (e. g. well logging and materials metrology) and in emerging medical applications (e. g., Boron Neutron Capture Therapy). In particular, the replacement of radiological sources (urgent to minimize the risk of their malevolent use in dirty bombs) and global needs for nuclear safeguards and non-proliferation verification in an environment of expanding nuclear industries require transformational increases in operational capabilities by orders of magnitude in critical metrics including
• system compactness
• output yields (e. g., $>10^{11}$ n or gamma/s)

• operational flexibility (e. g., cw and nano-second pulsed operation)
• and lifetime (e. g., >20,000 h to replace Americium-Beryllium and Californium sources)

A sustained and focused R&D effort is urgently needed to develop the scientific and technological underpinnings of advanced neutron and gamma generators with game changing capabilities that enable their wide spread field use in highly strategic areas of national security, industry and materials science.

References:
-O. Waldmann and B. A. Ludewigt, “A permanent-magnet microwave ion source for a compact high-yield neutron generator”, AIP Conference Proceedings, 1336, 479 (2011)
-A. Persaud, et al., “Development of a compact neutron source based on field ionization processes”, J. Vac. Sci. Tech. B 29, 02B107 (2011)
- Q. Brian, et al., “Nuclear resonance Fluorescence for materials assays”, IEEE Trans. Nucl. Sci. 58, 400 (2011)
-“Radiation Source Use and Replacement”, National Research Council, 2008, ISBN: 0-309-11015-7, http://www.nap.edu/catalog/11976.html

3) Ultimate Ion Nano-beams

Ion nano-beams, with energies ranging from sub-keV to MeV, can enable exciting new science and technology developments in broad areas including disruptive concepts for computer and sensor technology, surface and materials structuring and analysis, and quantitative bio-nanotechnology e. g. through in vivo cell engineering.

Currently, ion nano-beams are available only for gallium and helium ions and there exists no solution for the reliable formation of ion beams with single digit nanometer dimensions and flexible energy. But if we were able to form beams of e. g. nitrogen or phosphorus ions focused to a spot size of 1 nm and a tunable energy (~0.1 to 5 keV), then we could create arrays of precisely placed dopant atoms and color centers in silicon and diamond and implement disruptive sensing and information processing techniques, including quantum computing ideas. These disruptive capabilities can be developed with a focused effort in applied accelerator R&D, requiring breakthroughs in ion formation, cooling, transport and detection.

References:
-T. Schenkel, et al., "A spin quantum bit architecture with coupled donors and quantum dots in silicon", http://arxiv.org/abs/1110.2228
-J. J. L. Morton, et al., Embracing the quantum limit in silicon computing, Nature 479, 345 (2011)
-A. M. Tyryshkin, et al., Electron spin coherence exceeding seconds in high-purity silicon, Nat. Mat. 11, 143 (2012)
-G. Fuchs, et al., Excited-state spin coherence of a single nitrogen-vacancy centre in diamond, Nat. Phys. 6, 668 (2010)

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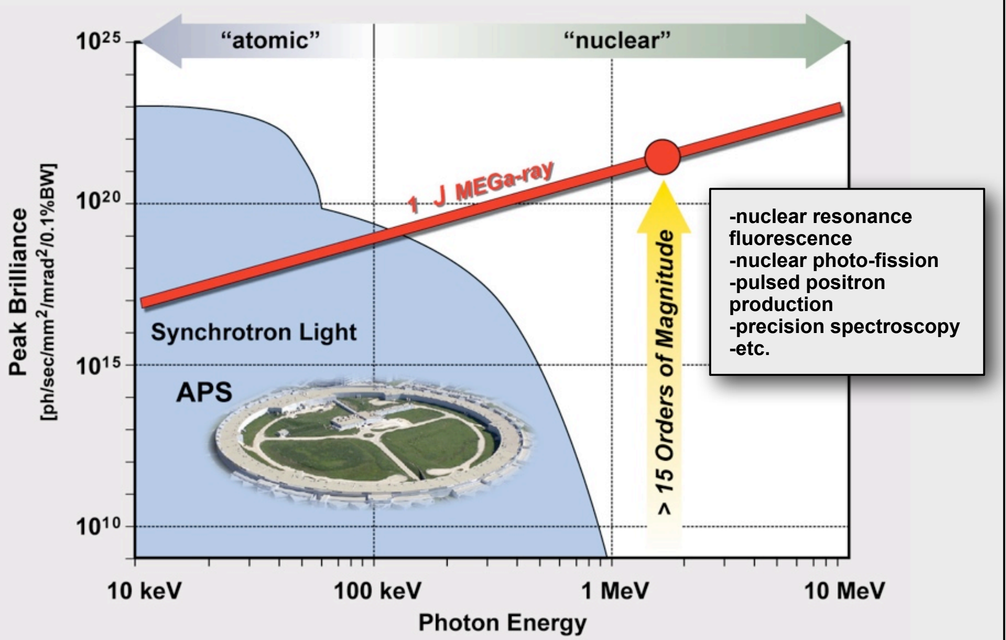
Appendix 10

Lawrence Livermore National Laboratory – MEGa-ray Technology

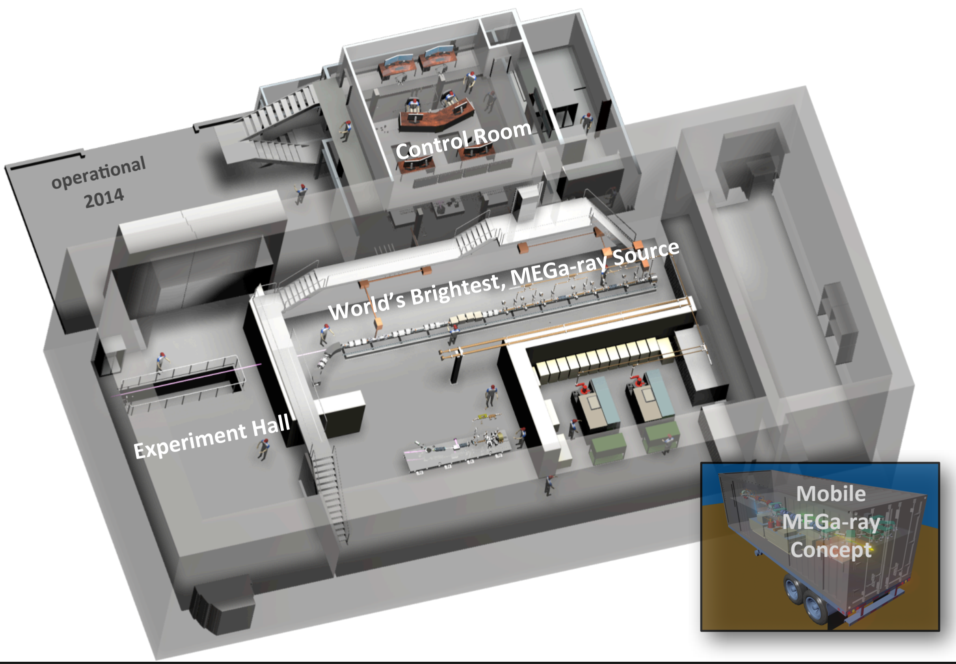
LLNL's Mono-energetic Gamma-ray (MEGa-ray) Technology is Transformational

MEGa-rays are a Revolutionary Leap in Light Source Capability



New Solutions to National Missions are Enabled by MEGa-rays

LLNL's Nuclear Photonics Facility



LLNL's MEGa-ray technologies and facilities will provide:

- A world-leading, tunable, mono-energetic, ultrahigh brightness & flux gamma-ray user capability
- A unique, isotope-specific ability to rapidly detect, assay and image the contents of thick objects (LLNL patent)
- A testbed for development of fundamentally new solutions to a wide array of nuclear and materials issues that span multiple agencies and organizations
- A platform for the development of compact, mobile and field deployable MEGa-ray sources
- A catalyst for a renaissance in nuclear science and studies of fundamental nuclear physics with photon beams, i.e. Nuclear Photonics

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Appendix 11

Los Alamos National Laboratory – National Security and Defense

Editor's note: This document is from Los Alamos National Laboratory

National Security and Defense

Section 1: National Security Applications

National Security driven research in accelerator technology has tended to focus mainly on very high-peak or average-power systems or light-weight, very compact systems. This research has led to the development of new, innovative technologies, such as advanced control software (EPICS), megawatt RF tubes, and photoinjectors and has significantly advanced the state of the art in existing technologies, such as intense-beam physics codes and their experimental validation, superconducting technology, megawatt-class RF and accelerator components, RFQ's, and induction accelerators. Spin-offs of these efforts have made and will continue to make significant contributions to other Office of Science departments. The rest of this section gives a subset of the wide-range of National Security accelerator related mission space and then covers a few of the successful defense national laboratory/industrial partnerships.

Nuclear Stockpile Stewardship

Future certification of the US nuclear weapons stockpile will require a predictive understanding of dynamic materials response through simulations of full-scale weapons systems. These simulations will rely on accurate constitutive models of material dynamics at the component level including understanding the effects of kinetics in delaying dynamic phase transitions, developing models for explosives safety, understanding materials casting processes, and the dynamic behavior of nuclear materials. Development, testing, and validation of these constitutive models is needed as weapons systems materials age and are modified to meet future stockpile needs, or new processes are discovered to be important in nuclear weapons performance. The validation of new models for nuclear weapons performance, as well as for new high performance materials, will require state-of-the-art imaging of reduced scale up to full-scale systems. To do so requires relying on techniques such as multi-time electron or proton radiography, or coherent-imaging techniques using high-energy photon beams (XFELs) generated by accelerator drivers.

Active Interrogation Systems

Active interrogation (AI) systems are needed to detect the illicit transportation of nuclear and radiological materials. Production of the interrogation particles, either protons, neutrons, gammas, or muons, require innovative developments in accelerator technology. The highest priority AI systems are either compact, short range or long stand-off. The compact short-range systems must be very compact and transportable. The long stand-off systems will rely on very high-energy, 100's of MeV to GeV, particles. High energy proton and muons can be transported kilometers with an acceptable loss. Muons are uniquely suited to probe phenomena of interest to national security that are not well addressed by electrons, photons, or protons. In many cases, muons provide unique and unambiguous material signatures. The use of muons for homeland security applications creates a new window of need and opportunity to exploit accelerated muons in a wide range of homeland security applications – as well as the more obvious basic science and industrial applications.

Directed Energy Applications

The need for speed-of- light weapons came to prominence during the Strategic Defense Initiative. Although the need for ballistic missile defense has a lessened priority, the need for cruise missile defense has gained prominence given the likely spread of this weaponry to aggressor nations. The Navy has identified a CW, MW-class, IR FEL as a future weapons system for ship defense. It provides naval platforms with a highly effective and affordable point defense capability against surface and air threats, future anti-ship cruise missiles or swarms of small boats. The advantages of an FEL are that it provides an unlimited magazine with speed-of-light delivery. The Navy states that the FEL is a revolutionary weapon that will transform how the Navy fights future battles. The Office of Naval Research is currently funding an Innovative Naval Prototype (INP) program for FEL technology which will demonstrate scalability of the necessary FEL physics and engineering for an eventual MW-class device.

High Power RF Applications

Electronic equipment is susceptible to attack through electro-magnetic pulse (EMP) and high-power microwave (HPM). EMP and HPM are closely related, with EMP being the ultra-wideband limit of HPM. Damage to electronics and electrical components from an EMP induced by a nuclear explosion was observed even at the first nuclear test in 1945. HPM source requirements are similar to high-power microwave tube requirements for driving accelerators and are used for defense applications such as vehicle stopping at checkpoints to thwart suicide bombers, induced IED pre-detonation for road clearing, and command and communication disablement through HPM payloads on missiles or unmanned aircraft. Additionally, there is an anti-personnel application (discrimination) using millimeter waves in the 90-100 GHz regime, as alternative non-lethal option.. The development of high-power microwave tubes needed for such applications requires the ability to produce and control intense electron beams at comparatively low energy, and this effort has driven the development of intense beam modeling tools, along with high power components of use throughout the accelerator field.

Spallation Neutron Sources

Spallation neutron sources are used to measure nuclear cross sections, to develop single event upset (SEU) resistant electronics, and provide neutrons for weapons program isotope production. Precise cross-sections for fission in nuclear materials, as well as cross-sections for capture on actinides are key to understanding nuclear weapons performance. Accelerator-based capabilities exist to measure these at both low and high neutron energies. The “overlap” neutron energy range from 1 keV to 2 MeV is important for weapons radiochemical measurements, but is a very difficult region to probe experimentally.

X-Ray Bremsstrahlung Sources

NNSA has determined that Bremsstrahlung sources are part of its roadmap for SNM movement detection program, and similar programs are part of DTRA’s portfolio. For NNSA, the Nuclear Emergency Response Team (NEST) responds to nuclear emergencies. One of its teams, the Accident Response Group (ARG), is responsible for damaged US weapons, and other, the Joint Technical Operations Team (JTOT), would respond to a terrorist weapon. Both teams need portable radiography capabilities. Other applications include field certifying integrated circuits (such as for DAPRA’s TRUST program) and deployed radiography of suspected SNM contraband.

Nuclear Assay for Counter Proliferation

Spent nuclear fuel from commercial and research reactors has plutonium and enriched uranium that must be safeguarded to avoid diversion for military or other applications. Techniques are being developed to quantify the amount and type of fissile material in spent fuel rods removed from reactors. One technique uses an electron or proton accelerator to produce neutrons within a lead slowing down spectrometer (LSDS). A spent fuel rod placed in this environment will emit time-dependent fast neutron spectrum from nuclear fission that can be detected to measure the amount of fissile isotopes in the rod.

Nuclear Weapons Neutron Effects Testing

The DOE has need to test the susceptibility of electronic device performance to short bursts of high-dose neutrons. Historically these tests were conducted at the Sandia Pulse Reactor, but this reactor was shut down several years ago. This type of testing could be performed at an accelerator-driven neutron source, where a neutron spallation target is neutronically coupled to a subcritical assembly. A short burst of protons delivered by an accelerator or storage ring can produce an intense, short burst of neutrons for component testing. This application is best served by a large proton accelerator facility located at a national laboratory.

Government/Industrial Partnerships

National Security research has also led to successful government/industrial partnerships and with a resulting transfer of technology from the government to the private sector. The following are significant examples of technology transfer.

Dynapower and General Electric

For the Spallation Neutron Source (SNS) accelerator, Los Alamos developed a compact modulator technology that directly pulsed the cathode of the vacuum tube amplifiers. This technology is able to deliver long pulses (approximately 1 msec) at peak and average power levels of 10 MW and 1 MW respectively. Subsequent to the SNS development, has this technology was transferred to Dynapower Corporation, the world's leading independent manufacturer of custom power conversion equipment, and is actively supporting Dynapower corporation in the development of four modulator systems for the Proton Engineering Frontier Project for a 100 MeV, 1.6 ma proton accelerator supported by the Korea Atomic Energy Research Institute.

One of the innovations behind the development of the compact modulator technology for SNS was the development of high power, nanocrystalline transformer cores. Based on the SNS development, Los Alamos has teamed with GE to apply this core technology for the development of compact transformer systems in support of DARPA initiatives. The size and weight advantages of this design are driving interest from the Navy for the proposed All Electric Ship.

Carnegie Mellon, Spang Industries, University of Pittsburgh

Los Alamos has teamed with Carnegie Mellon, Spang Industries, and the University of Pittsburgh to develop advanced solar power conditioning equipment. This project is funded by the ARPA-E and draws on previous government laboratory expertise to develop high efficiency polyphase resonant inverters using advanced magnetics. The polyphase resonant topology was originally developed for SNS converter modulator. The ARPA-E designs will push performance parameters to achieve the program goal of a 100 kW inverter weighing 25 kG. To achieve this Carnegie Mellon and Spang will develop a more advanced cobalt based nanocrystalline alloy that will be used for the power magnetics. From the magnetic material developed by Carnegie Mellon and Spang, Los Alamos will develop the appropriate power circuitry and transformer designs. The University of Pittsburgh will develop the economic models to implement the solar equipment in the U.S. market place.

Communications and Power Industries (CPI)

DOE has been supporting the development of high power IOT technology since the late 1980's. This technology combines the attributes of both klystrons and gridded tubes and promises large size and weight savings relative to conventional klystron technology. IOT technology has widespread commercial application in the TV broadcast arena where these power amplifiers provide approximately 12 kW of average power and up to 50 kW of peak power. As a result of this development, a 250 kW average power IOT was successfully delivered and operated on an accelerator. Also, LANL funded the development of a 750 kW peak power IOT at CPI in support of space based applications and the development of a 1 MW average power IOT. While these applications were all driven by accelerators, they represent the only R&D investments geared towards extending the power of IOT technology. As a result of these investments, IOTs have advanced to where they deliver up to 160kW of average power and are in service for high consequence military applications. They are also considered one of the enabling technologies for the Navy FEL program.

The Boeing Co. and Advanced Energy Systems

The Boeing Co. is the lead to develop the Free Electron Laser Innovative Naval Prototype (FEL INP) for the Office of Naval Research. Boeing has been successful at tapping the expertise that currently exists at the DOE laboratories to design this high-power FEL prototype. This expertise includes high-average-power accelerators, both normal conducting and superconducting, energy recovery linac as well as a myriad of supporting technologies such as high-power RF, controls, etc. Boeing's success at teaming with the national laboratories such as LANL, Jefferson Lab and Argonne on the FEL INP bodes well for the transfer of accelerator technologies from the DOE labs to industry.

Advanced Energy System (AES) and LANL collaborated on a challenging task of designing, fabricating and assembling the high-average-current normal-conducting radio-frequency (NCRF) gun. This project involved successful technology transfer from LANL to AES on both the design and manufacturing of this NCRF gun. The sophisticated cooling channels were designed by AES in full coordination and real time with the physics design effort at LANL. This well-coordinated design effort is the reason why the NCRF gun works exceedingly well at the end of the fabrication and assembly phase.

Section 2: Technology Gaps

High Brightness Beams

A broad range of new materials are needed for military applications that can be enabled by the combined high resolution probes from particle and photon beams. Examples of such materials include high explosives and high strength armor where typically an understanding and control of micron-scale features is critical to the material performance. Energetic proton and electron beams that can penetrate thick samples are used for high resolution radiography, augmented by FEL-produced coherent photons, to yield ultra high-resolution, images of the internal characteristics of the materials under dynamic conditions. Such a beam facility would lead to the development of materials tailored at the microscopic scale for specific applications. The broad-based need for such material development has driven a need for high brightness particle beams and very short wavelength x-ray Free Electron Lasers.

The development of new accelerator and beam technologies are key to cost-effectively enhancing existing systems and significantly improving present performance by delivering high-energy, high-charge, low-emittance proton and electron beams. In addition to more conventional accelerator technologies, an alternative technology relies on laser-driven acceleration as a source of primary beams for radiography and to create secondary probe beams to study physical processes such as warm dense matter (WDM) and measurements of equation of state (EOS), both of interest to the nuclear weapons, plasma physics, and fusion communities.

High Average Power Beams

The production of high average-power beams using electrons, the FEL, or protons, Neutral Particle Beam or Accelerator Production of Tritium, has been driven by national security missions. High average power ion beams are also needed for weapons-related isotope production. Research leading to the demonstration of a high-average-current superconducting RF electron gun will have significant impact on the design of the next-generation high-power FEL. The injector technology gap includes delivering a robust long lifetime photocathode with reasonable (> 1%) quantum efficiency capable of delivering amperes of current. Electron beams having peak currents in the several thousand ampere range are needed as drivers for full-scale radiography of weapons components. The generation and propagation of such beams requires the development of components that can handle megawatts of power and transport the resultant beams with very low loss.

The energy recovery linac and beam transport designs require higher fidelity numerical simulations, particularly for beam halo production and coherent synchrotron radiation (CSR) effects. There are additional technology gaps for diagnostics, particularly for non-intercepting diagnostics for high-current beams and for halo measurements. In the highest intensity particle beams generated to date, the evolution and confinement of a diffuse particle halo actually determines the beam intensity limit due to losses which in turn can lead to radiation and activation of the beam hardware. High average power beams are particularly vulnerable in that even a halo that may be many orders of magnitude smaller than the beam core is sufficient to limit beam operation. The understanding of the mechanisms that generate halo is lacking at the level of dynamic range required to control the phenomenon.

New Accelerator Systems for Active Interrogation

The active interrogation (AI) mission requires the development of two types of systems: compact, mobile proton and other ion accelerators, and high energy proton or muon beams. The compact systems are typically lower energy, less than 50 MeV and at modest currents, less than 10 mA, but need to be light enough to be carried by a few people and small enough to be transported by pick-up truck. The high energy systems are typically greater than 500 MeV. To enable the use of muon interrogation requires significant advances in the efficient capturing, cooling and then acceleration of muons, and advances in high-gradient, efficient accelerator technology.

Laser-plasma accelerators offer the potential for a significant reduction in size for high-energy beam production. The simulated electric fields for these accelerators are PetaV/m for protons and ~ GeV/m for heavier ions. Success in high-energy laser proton acceleration rests on a new paradigm, and volumetric interaction with relativistically transparent, over-dense targets. Significant progress has been achieved in accelerating both protons and heavy ions based on these novel processes.

High-Power RF Sources

New high-power, efficient and compact microwave sources are required to cover the range from 0.1 GHz to the Terrahertz regime.

Bremsstrahlung Sources

Currently, commercial systems exists at both low X-ray energies for imaging electronics systems and higher X-ray energies for radiography of denser nuclear material, but these systems are too heavy to be man-portable (for example, the 6-MeV Varian Linatron M6 which produces 800R/min weighs about a ton). The state-of-the-art in lightweight commercial systems at these X-ray energies is the JME PXB6 betatron, capable of producing doses > 3R/min at 1 m, but still weighs over 300 lbs. Technology gaps needed for NNSA and DTRA programs include lighter weight systems that are tunable, and may include an integrated RF and linac as well as advances in lightweight pulse power.

Modeling and Simulations

Modeling and simulation capabilities have played a significant role in enabling accelerator advances for defense applications. These capabilities have been applied to understanding fundamental beam physics, as design tools including evaluating the expected performance, and for evaluating performance of operating systems. Advances in computational speed, reductions in cost of computer memory, and on-going developments in software and computer architectures have all contributed to ever-increasing more realistic accelerator simulation capabilities. Recent developments in multi-processor computing including the move towards exascale computing and the development of inexpensive, yet very-high-performance desk-top systems such as those based on GPU technology should be exploited. Development of these systems will allow routine multi-particle beam simulations with realistic numbers of particles per bunch, allowing exploration of beam physics dominated effects at a level not yet explored. The understanding and mitigation of beam loss and beam-halo effects in high-average-power ion accelerators, where details at the one part in 10^8-level or better is required, would immediately benefit.

Advances in fast, inexpensive computing also enable needed improvements in near-real-time accelerator modeling and control optimization that will improve operation of existing systems as well as enable the successful deployment of evermore complex accelerator-based interrogation and weapons systems. The use of real-time accelerator control system and diagnostics information to drive high-performance modeling and simulation capabilities coupled with fast, intelligent controls optimization algorithms has not yet been exploited.

Reliability, Availability, and Maintainability, and Inspectability (RAMI)

Large complex accelerator systems and compact systems that need to be deployed in the field can benefit from system engineering approaches such as Reliability, Availability, Maintainability and Inspectability (RAMI) analysis to ensure dependable and reproducible performance. Through a well-integrated design approach, RAMI modeling capability along with world-wide accelerator system RAMI data can be exploited to improve end-product performance and reliability. Such tools were previously developed for the NNSA-funded Accelerator Production of Tritium (APT) project in collaboration with industry (Grumman/Advanced Energy Systems) and were used to validate the design. There has been a resurgence of interest in using this approach for the design of the European Spallation Neutron Source (ESS) and potentially to improve the design of accelerator-driven systems for energy production that must maintain very low numbers of beam interruptions to minimize target/reactor stresses and reliable electrical power to customers. Investments could be used to develop a standardized, modern RAMI modeling approach that would potentially benefit most new projects.

Spallation Sources

The application of innovative accelerator and beam transport technology has the potential to enable continuous coverage of the neutron energy range from a single source from 10's of eV to several MeV with significantly increased neutron intensity and improved energy resolution. Realization of such a source also has relevance to other national security mission areas including nonproliferation, criticality safety, energy security, and for basic nuclear physics and astrophysics.

Beam Diagnostics

As the current state of beam brightness and power has been increased to unprecedented levels, diagnostics which are capable of measuring the beam phase space have become increasingly challenging. At present there are no techniques that can precisely determine the beam phase space density for the brightest beams, e.g. for the current generation of X-ray Free Electron Lasers. The further development of this field will be greatly aided by the development of beam diagnostics which can be used to facilitate the complex phase space manipulations that are required.

Section 3: Research to Address Gaps

Very High-Brightness Electron Beams

The next generation of XFELs will require an order of magnitude higher brightness electron beams than have been achieved to date. Coherent synchrotron emission (CSR) is a significant brightness limiting mechanism for the very high brightness electron beams required for XFELs. Modeling and measurements on existing machines is required to fully quantify the limitations imposed by CSR.

New methods are required to measure the beam phase space volume, or emittance, of the brightest beams, namely those in the current and proposed generation of X-ray Free Electron lasers. Diagnostics must to built that can measure the ultra small emittance values of 0.1 mm-mrad and the temporal length of the ultra short bunch pulses that are anticipated in these devices. Both concept development and experimental demonstration are required.

XFELs and active muon interrogation will benefit from emittance partitioning or exchange schemes, in which excess transverse emittance can be relocated into the longitudinal dimension.

High Power Systems

The demonstration of high-power, high-gradient superconducting components is required, such as > 50 MV/m superconducting cells or alternative accelerating structures that operate at > 4 K, MW-class power couplers, high-efficiency MW IOT RF tubes. MW class beams requires research directed toward the generation and the understanding of beam halo generation during the propagation of ampere beams so the beam intensities can be pushed to the required ever-higher levels.

Ion and electron beam systems have benefited significantly in recent years by the application of superconducting cavity technology, which has helped improve both the beam performance of these systems and the operating efficiency. The development of high efficiency, higher-gradient superconducting systems is essential since operating cost and maintenance are significant issues of any high-power system. Advanced photocathode concepts are also required. Alternative superconducting materials, such as magnesium diboride (MgB_2), suggest that the critical field limit can be exceeded and that accelerating gradients as high as 100 MV/m may be achievable. Cavity shape optimization and eliminating seams through new fabrication techniques may also help in reaching higher gradients.

Electron systems that deliver high average power today primarily rely on induction linear accelerator technology using pulsed-diode cathodes to generate the high peak-current beam. Innovation in induction cell technology to reach higher fields and longer pulses is needed. Significant improvements are needed for pulsed cathodes capable of reliably producing high current densities at lower diode voltages (high efficiency) are needed to generate high-quality (low emittance), high-current beams for electron radiography.

At the present time, high-power RF sources are limited by beam dynamics and power density issues to given power limits that generally decrease with increasing frequency. Research is needed in the physics of intense, low-energy beams to determine how to extend the present limits and improve efficiency.

Both large-scale numerical models are needed along with large dynamic range experimental verification.

Exascale Computing

Particle simulations are now at the level of modeling every particle within a beam, though the calculations are not yet comprehensive; typically the collective effects that often limit the beam intensities are not computed fully self-consistently. Taking such models to the next generation of parallelism and speed, the so called exascale, should enable a much higher quality and fully self-consistent model of a given beam application. The most important physics that is not now being modeled correctly is 3-D space-charge in photoinjectors, wakefields, and CSR. Modeling CSR correctly is the most difficult of these problems, and limitations to 1-D approaches have now been identified. Noise that seeds the microbunch instability (MBI) and the MBI gain itself both require energy-dependent CSR models.

Applied System Engineering

Fielded systems in critical applications must have a high expectation for full functionality. New technologies need to be developed that is focused on improving the reliability and ease of maintenance for accelerator systems.

Fast Kickers

Through a process dubbed “pulse stacking,” the number of protons per pulse in a storage ring can be enhanced significantly while allowing variable pulse time structure to optimize time-of-flight measurements to improve experimental signal-to-noise ratios. Conceptual studies to realize this capability have been done but there are several technology challenges. Several new techniques and devices need to be developed including rapidly-tuned RF cavities and their control, fast-rise extraction kickers, multi-frequency resonance control, beam stability, and multiplexed beam transport. Results of these advances will be of great interest to the accelerator-technology community.

RF Sources

HPM systems require the development of systems with the ability to provide short (10 to 30 nsec) pulses at high repetition rates to increase the likelihood of significant effect, at powers of 100s of MW to 1 GW. Target frequency susceptibility tends to be ~ 10%, so narrowband RF sources need to be frequency swept for longer pulses.

Technology gaps needed for NNSA and DTRA programs include lighter weight systems that are tunable, and may include an integrated RF and linac as well as advances in lightweight pulse power. R&D is required for: air-core transformers, compact diode-directed solid-state Marx technology, higher energy storage capacitors, integrated pulse power and linac technology, development of compact higher frequency (W-band) sources and linacs to further reduce size and weight, electron diode systems that have optimized beam focusing over wide voltage ranges (one-half to several MeV).

Alternative Particle-Accelerators

New compact proton superconducting cyclotrons based on advanced design and construction techniques have several applications. One application requires a compact cyclotron that operates up to 20 MeV but weighs less than 500 lbs. Another application requires a transportable GeV cyclotron.

Laser-driven sources have designs for a range of self-consistent laser parameters (energy, intensity, and pulse length) that could provide a specified proton beam. However, the optimal laser for this application does not exist so we can simply test that design point. The codes need to be validated with experiments in relevant broad regions of laser performance parameter space.

The practical implementation of muon interrogation requires further development of the collection and acceleration of muons.

Goes to the Energy Group:

The campaign of ignition experiments has begun at the National Ignition Facility (NIF). These experiments are stimulating a resurgence of interest in inertial fusion energy systems, including Heavy Ion Fusion (HIF). Although much progress was made in the past, there has been no recent significant funding to support accelerator technology develop for HIF. There are now new opportunities for experimental collaboration on beam physics and accelerator research focused on developing the needed integrated systems for reliable cost-effective energy production using HIF. Recent advances in accelerator science that can be leveraged and have a potential impact on HIF include: long-term operation of large heavy-ion accelerator facilities with high availability and high reliability; higher fields have been demonstrated in superconducting magnets(the operating range has doubled); developments in control systems and diagnostics for high-intensity accelerators; the ability to simulate complex beam and target systems has improved dramatically – simulation codes have been validated on a range of accelerators and basic science experiments; driver-scale ion sources with adequate beam parameters have been demonstrated for single beams, including high charge state ions. To move closer to the realization of HIF as a potential energy source will require new advances in both induction and RF accelerator technologies, including hybrid systems and acceleration of multiple beams. Major challenges also exist in better understanding limitations due to space charge, emittance growth, beam-gas and beam-plasma interactions that all must be sufficiently controlled throughout the HIF driver accelerator.

US energy policy should also support other alternative methods of producing energy including the development of sub-critical accelerator-driven energy systems (ADS). Long-term energy security and greenhouse gas reduction has motivated a return to nuclear energy. Recent events in Fukushima highlight the danger of nuclear waste in spent fuel rods that are temporarily stored at nuclear reactors around the world. Solving the nuclear waste problem requires burning long-lived transuranic actinides (neptunium, plutonium, americium and curium) that exist in spent fuel. There is significant recent progress in the development and prototyping of technology, as well as integrated demonstration capability in both Europe and Asia. The US is lagging, although much of the early technology was developed through US DOE/NNSA funding.

Most activities world-wide are focused on proton-driven systems, however other alternatives such as high-average-current electron accelerators can also produce the necessary fast-spectrum neutrons for transmuting these long-lived actinides. One of the major advantages of this approach is that it does not require a large facility (such as proton-based ADS) and it can be designed into a compact subcritical assembly that offers neutron multiplication to compensate for the relatively low neutron production rate from the (gamma,n) process. A subcritical ADS has the advantage over critical reactors in that it can operate with fertile-free fuel, thus reducing reprocessing costs and waste streams, and may be a "game-changer" in the utilization of a subcritical burner.

A US ADS test bed or demonstration facility should be pursued. A natural location for such a facility would be a US National laboratory where infrastructure for high-power beam operations, an appropriate-category nuclear facility could be supported, and existing centers of technical excellence in accelerator technology already exist. Advances are needed in several key accelerator technology areas including SC technology (higher gradients and lower operating temps) and improvements in reliability through advanced controls applications, state-of-the art simulations, and beam diagnostics.

Goes to the Medical Group:

Note that this is not only a medical issue but a National Security issue

Molybdenum-99 Production

Technetium-99m is a metastable nuclear isomer used in ~ 20M diagnostic medical procedures per year (accounting for roughly 85% of all nuclear imaging procedures). Currently, technetium-99m is generated by the decay of molybdenum-99 (Mo-99), which has a half-life of about 66 hours. Mo-99 is typically produced in the core of a nuclear reactor, most of which use highly enriched uranium (HEU), which is a proliferation risk acknowledged by NNSA. This has lead NNSA to fund the development of alternative technologies through the Global Threat Reduction Initiative, which includes research on reactor-based technologies using low-enriched uranium (LEU) and accelerator technologies. Both proton-driven and electron-driven production of Mo-99 have already been demonstrated through this program.

Technology gaps exist that require accelerator development for producing the large quantities of medical 99mTc required in the US. Advances in these areas will benefit not only Mo-99 production, but production of other medical radioisotopes as well. R&D is required for

- Higher average current cavities
- More efficient accelerators
- Reduced cost accelerators
- Advances in high power target design to minimize the required amount of expensive target material.

- Advanced beam diagnostics, both intercepting and non intercepting. A particularly important diagnostic is simultaneous measurement of IR and OTR on the beam window.

- Characterization of the branching ratio between the metastable and ground states for high spin deficit photonuclear reactions for optimizing design (94Mo(γ,n)93Mo vs 93mMo and 206Pb(γ,2n)204Pb vs 204mPb are examples). These branching ratios are extremely difficult to measure and are not well described by theory. These reactions are difficult to measure in these particular reactions because the ground state is either very long lived in the case of 93Mo, or stable in the case of 204Pb.

Office of High Energy Physics Accelerator R&D Task Force Report

Appendix 12

Sandia National Laboratories –
SPARC Proposal

Editor's note: This document from Sandia National Laboratories is on their proposal to build SPARC.

Sandia National Laboratories is proposing to build a Short-Pulse Accelerator Research Center (SPARC). SPARC will include two pulsed-power accelerators in a single campus hosted by Sandia's Albuquerque, New Mexico site. The two accelerators, named SPARC-E and SPARC-Z, have been designed to meet the nation's long-term needs in radiation effects science (RES) and high energy density physics (HEDP), respectively. The pulsed-power architecture for both accelerators will be based on scaled versions of new linear transformer driver (LTD) technology being tested today. The LTD architecture employed by SPARC is a new approach to creating high-current or high-voltage power devices. The most significant advance in pulsed-power energy storage since the invention of the Marx generator in 1924, LTDs are a scalable approach to pulsed power in which simple components are assembled into larger modules. The modules can be combined in different ways to produce electrical currents that are not only higher than present pulsed-power approaches, but also reduce accelerator operations stress nearly 50-fold.

While the specific parameters of the two accelerators differ, their engineering design, manufacturing, testing, and environmental safety and health requirements have significant overlap, thereby reducing the overall project cost and timeline. There is also significant overlap in the scientific and engineering expertise required to build, maintain, operate, and diagnose the two machines.

SPARC-E is a high-voltage short-pulse (130 ns) electron-beam accelerator. It will produce radiation environments needed to certify future stockpile components for hostile environments.

SPARC-Z is a high-current variable-pulse (130-1000 ns) accelerator capable of coupling to a variety of target loads for both RES and HEDP applications. It will be capable of producing megajoules of 1-10 keV x rays. This far exceeds that which is currently available today in the laboratory. Similarly, the facility will be able to achieve controlled energy densities in large volumes many times in excess of what are possible today. Large samples (i.e., with diameters on the order of a centimeter) of critical nuclear materials will be compressed isentropically to pressures and temperatures of interest, reducing the amount of uncertainty that results from extrapolating from what we can presently measure. Finally, higher-risk and less-mature ideas being studied in fusion and radiation science have the potential to further enhance the usefulness of SPARC-Z beyond what we can confidently predict with existing codes.

SPARC-E and SPARC-Z will anchor a world-class campus that will bring together the nation's best scientists and engineers to work on RES and HEDP. The SPARC accelerators will be the world's largest and most powerful pulsed-power accelerators, which will use a next-generation LTD architecture that will help the United States maintain its leadership in pulsed power. Moreover, the unprecedented laboratory pressures and yields will enable these accelerators to not only meet the certification and science-based stockpile-stewardship needs of the country, they will also create opportunities for new science and engineering discoveries. The resulting collaborations between researchers at the weapons laboratories and universities to harvest the fruits of this project will ensure a steady stream of talented scientists eager to work at our national laboratories and knowledgeable independent reviewers of our work. For this reason, we believe SPARC will surely benefit our nation in additional ways that we may not fully envision today, just as "a mighty flame follows a little spark." (Dante Alighieri)

Pulsed power accelerators have a long history of providing the means for certifying and testing the stockpile that goes back over 50 years. The high efficiency of energy transfer from storage capacitors to a target load makes them a relatively inexpensive means for producing high x-ray yields and driving large samples to high pressures.

The high energy density science community has developed many *high-current* pulsed power accelerators over the past 50 years. [We define a high-current accelerator to be one that delivers in excess of 1,000,000 amperes (1 MA) to a physics target load.] The prime-power source of a *conventional* high-current machine consists of one or more Marx generators. A Marx is an array of n capacitors that are charged in parallel to the same voltage V, and discharged in series (using switches) to create a total voltage equal to n*V.

The refurbished Z facility at Sandia is presently the world's largest and most powerful pulsed-power accelerator, and represents the state-of-the-art of conventional Marx-based technology. The accelerator is 33 meters in diameter, stores 20 MJ of electrical energy, and delivers 85 terawatts (TW) of electrical power (5-7 MJ) to its vacuum chamber. Depending on the inductance of the target load, the electrical power results in as much as 27 MA of current flowing through the load. By comparison, the National Ignition Facility, the world's largest laser facility, delivers up to 1.8 MJ of green laser light into its vacuum target chamber out of an initial stored energy in its capacitors of 400 MJ. It is for this reason that pulsed-power technology is preferable for applications requiring large energies or doses.

The refurbished Z includes 36 pulsed power modules. The prime power source of each module is a Marx generator, and the energy from each Marx is passed through four stages of pulse compression before it reaches the target load at the center of the machine. These stages compress the energy in both space and time and increase the energy density (equivalent to pressure) of the electrical power from $2x10^5$ J/m^3 ($2x10^{-6}$ Mbar) to ~10^{13} J/m^3 (100 Mbar). This large pressure is used to drive experiments to high energy density conditions (>1 Mbar).

A Marx generator is, in essence, an LC circuit, i.e., a circuit that consists of an inductor (with inductance L) connected to a capacitor (with capacitance C). The characteristic discharge time of the current pulse produced by such a circuit is approximately $2(LC)^{1/2}$. The width of the current pulse produced by a Z Marx is 1.5 µs. Experiments conducted on Z require that a linear combination of 130-ns-wide current pulses, one generated by each of Z's 36 modules, be delivered to the load. To produce a 130-ns pulse, each module uses four stages of pulse compression to shorten the pulse produced by its Marx generator.

The pulse-compression hardware includes four pulse-forming transmission lines, a laser-triggered gas switch, and two sets of self-closing water switches. To achieve the highest peak currents, the 36 modules are triggered simultaneously so that their energy is combined into a single, 130-ns-wide current pulse. For shockless dynamic materials experiments, the discharge from each of the 36 modules are staggered in time to produce a specific current pulse shape that increases the drive pressure on the sample without creating a shock in the material. Creating the exact current pulse shape needed for each experiment requires precise timing of each module, achieved through a combination of two independent Marx trigger systems and 36 independently timed laser-triggered gas switches. In this way, current pulses of approximately 1 µs in duration have been produced to support experiments.

However, the pulse-compression stages significantly decrease the efficiency of the refurbished Z accelerator. The stages also increase the effort required to maintain the machine, and make it more difficult to perform an accurate and predictive circuit simulation of an accelerator shot. Furthermore, the design of Z also includes a number of impedance mismatches, which create reflections of the power pulse within the accelerator. Such internal reflections also decrease accelerator efficiency, damage the accelerator (after the primary power pulse has been delivered to the load), and make it more challenging to simulate an accelerator shot. For these reasons, scaling conventional accelerator architecture to current and/or voltage levels beyond that of the refurbished Z is not the optimum path forward.

The SPARC-E and SPARC-Z accelerators will be based on a *next-generation* architecture that improves upon existing conventional pulsed-power accelerators. While a number of architectures have been proposed for the design of future high-current pulsed power machines, we believe the most attractive approach is based on the new LTD architecture. The architecture uses two simple design concepts: single-stage pulse compression and impedance matching.

Like a Marx generator, an LTD is also, in essence, an LC circuit. In conventional pulsed-power accelerators, the pulse width $2(LC)^{1/2}$ of the Marx generators is long (e.g., 1.5 μs in the case of Z), and shorter pulses are obtained through multiple pulse-compression stages. In the proposed SPARC LTD architecture, the pulse width $2(LC)^{1/2}$ is an order of magnitude less, approximately 130 ns, hence no additional pulse compression stages are needed. This approach eliminates the inefficiencies and most of the other difficulties associated with the pulse-compression stages typically employed by conventional pulsed power machines. The shorter LC time constant is obtained by reducing both the inductance (L) and capacitance (C) of each circuit. The power pulse produced by the accelerator's LTDs is transported to the physics-package load by a system of impedance-matched transmission lines, to minimize reflections of the power pulse within the accelerator.

SPARC-E will be an 84-TW 1.5-MA electron-beam accelerator.

$P = 84$ TW

$E = 14$ MJ

$V_{e\text{-beam}} = 56$ MV

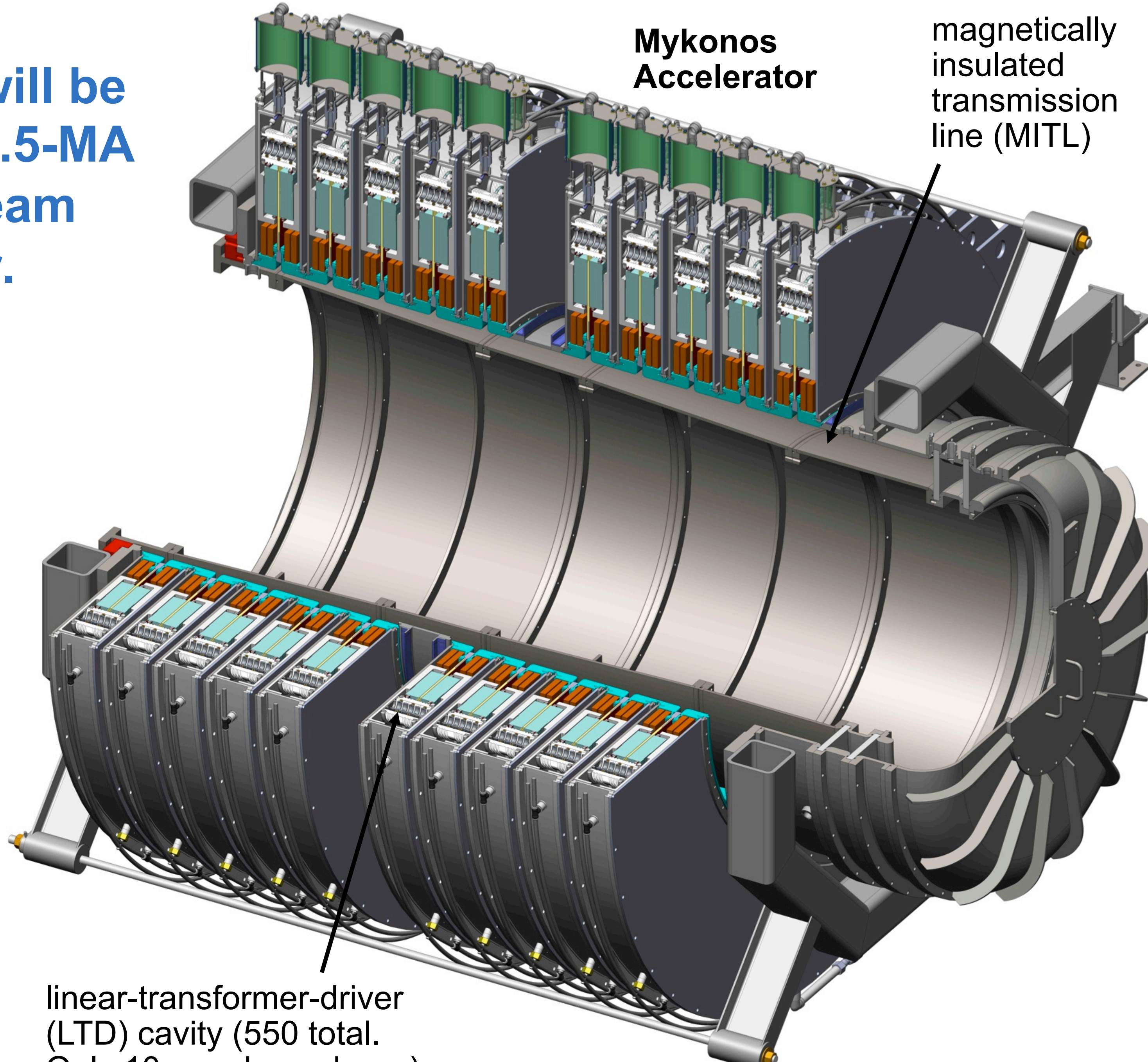
$I_{e\text{-beam}} = 1.5$ MA

$\tau_{FWHM} = 170$ ns

width = 3 m

length = 120 m

$\eta_{e\text{-beam}} = 75\%$



SPARC-Z will be an 800-TW 63-MA pulsed-power accelerator.

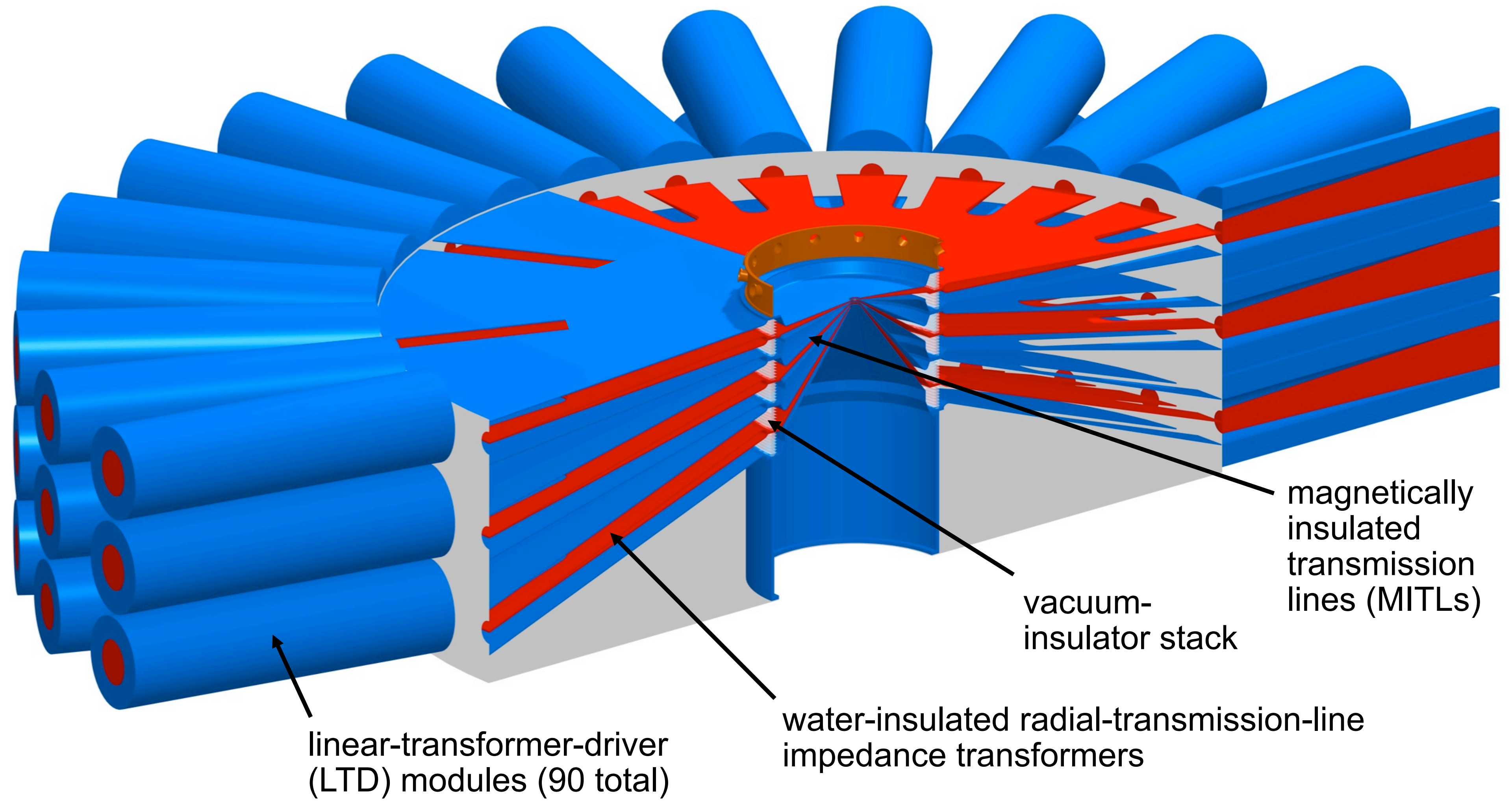
P = 830 TW
E = 130 MJ

V_{stack} = 16 MV
L_{vacuum} = 20 nH

I_{load} = 63 MA
$\tau_{implosion}$ = 110 ns

$E_{radiated}$ = 20 MJ
diameter = 50 m

η_{x-ray} = 15%



Office of High Energy Physics Accelerator R&D Task Force Report

Appendix 13

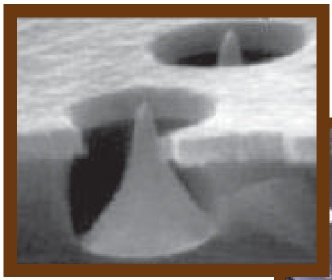
National Nuclear Security Administration –
Technology Roadmap

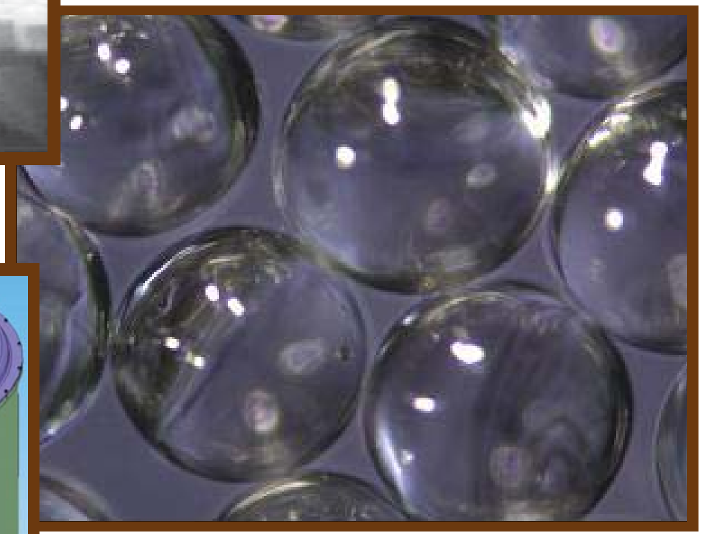
National Nuclear Security Administration
NA22-PDP-02-2007

Special Nuclear Materials Movement Detection Portfolio

Technology Roadmap

September 2007





Comments and inquiries regarding this document should be directed to Dr. Robert M. Mayo, NNSA/NA-22 at (202) 586-3937 or Dr. Daniel L. Stephens, Jr., NNSA/NA-22 at (202) 586-8329.

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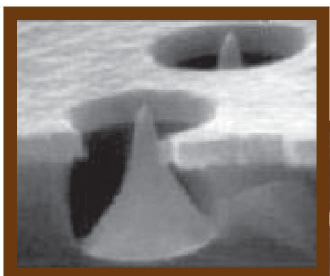
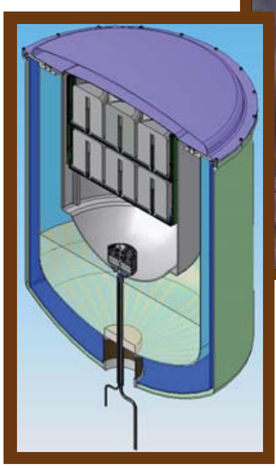
NA22-PDP-02-2007

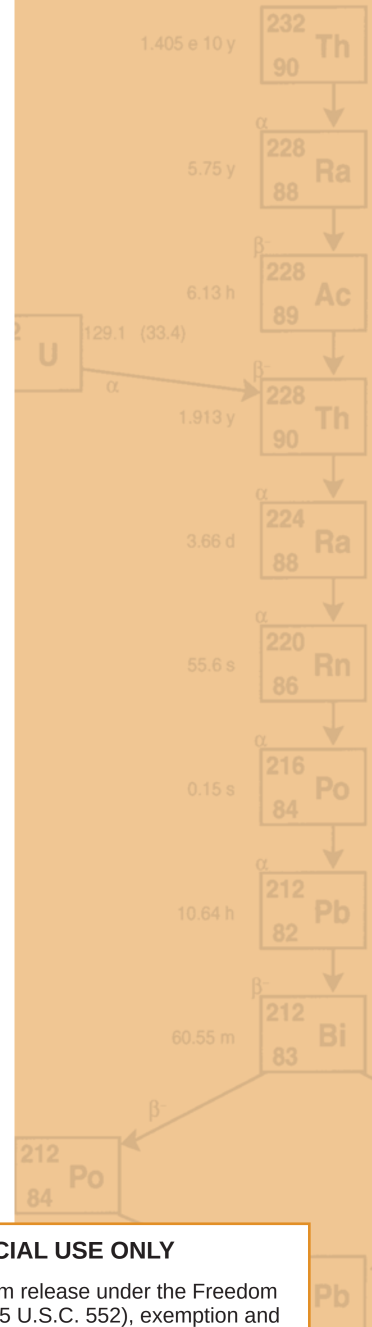
Special Nuclear Materials Movement Detection Portfolio

Technology Roadmap

September 2007







On the Cover

Sidebar image: The decay scheme for uranium-232 (^{232}U), an important signature for detecting highly enriched uranium (HEU).

Drawing: Advanced gamma-ray spectrometer composed of an array of high-purity germanium crystals that explores novel cryogenic cooling methods allowing new detection capabilities.

Small Photo: Micrograph of field-emission tip structures created in silicon designed to accelerate deuterons as part of a scalable, field neutron source for active interrogation.

Large Photo: Small ^{3}He-filled glass spheres. Embedded in a polymer matrix, these spheres can be fabricated into sheets for large-area thermal neutron detectors.

Office of Nonproliferation Research and Development (NA-22) Publication Release Form

Special Nuclear Materials Movement Detection Portfolio—Technology Roadmap

My signature indicates that I have reviewed and approved for limited release within the nonproliferation community the *Special Nuclear Materials Movement Detection Portfolio—Technology Roadmap* document, NA22-PDP-02-2007, which is part of NA-22's fiscal year 2007 Program Assessment Rating Tool requirement.

This document describes NA-22's technology roadmap for (a) defining technology development pathways that address requirements of the Proliferation Detection Program portfolio, (b) comparing technology development pathways to develop a portfolio investment strategy, and (c) identifying technology gaps that may serve as bases for future research and development.

Tjcerveny

Dr. T. Jan Cerveny
Assistant Deputy Administrator
Office of Nonproliferation R&D

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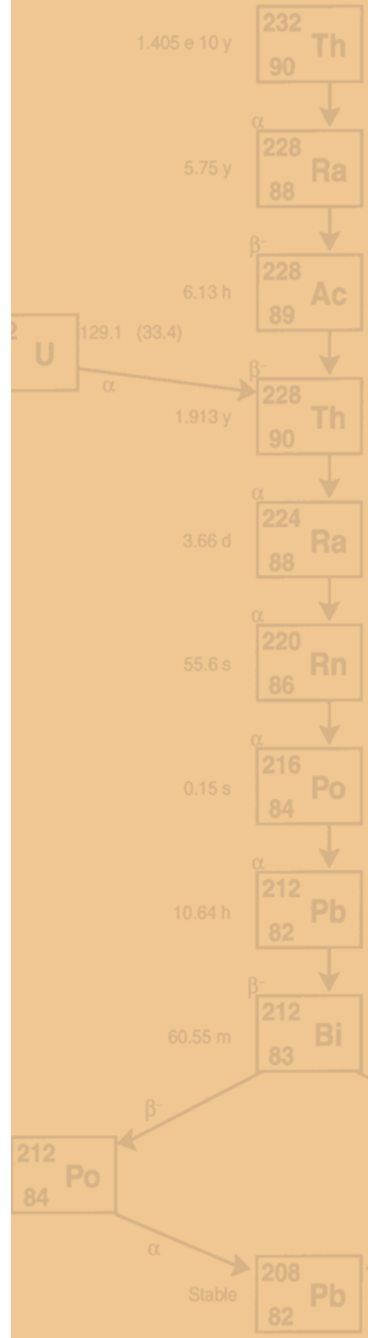

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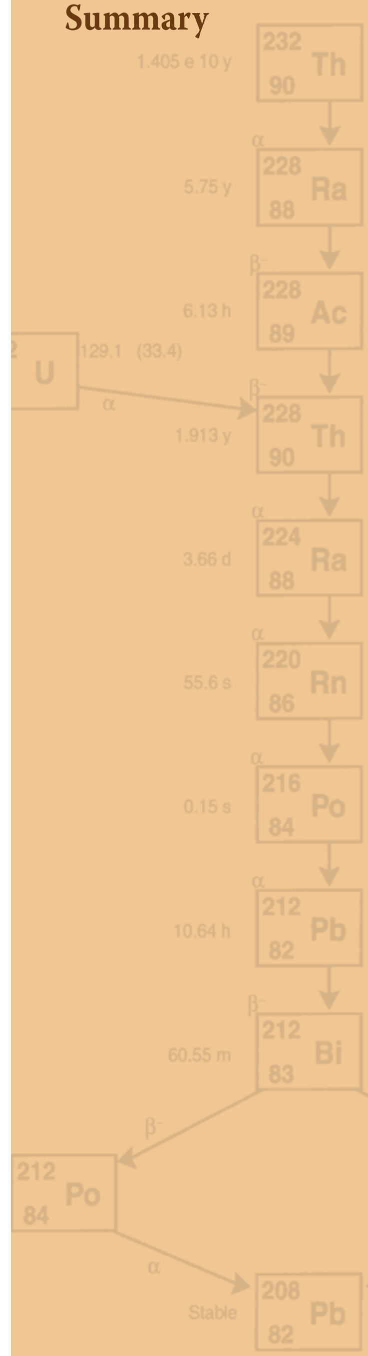


Special Nuclear Materials Movement Detection Portfolio—Technology Roadmap

The National Nuclear Security Administration's Office of Nonproliferation Research and Development (NA-22) Proliferation Detection Program has established a multi-year strategy in the form of program plans and roadmaps to conduct the research and development (R&D) necessary to demonstrate next-generation special nuclear materials (SNM) movement detection technologies. This strategy sets an aggressive schedule to plan, execute, and demonstrate mission-relevant components and technologies for SNM detection by the end of fiscal year (FY) 2013.

As a component of this strategy, this document develops a technology roadmap to be used to set funding priorities for R&D activities leading to capability demonstration against the portfolio's requirements as established in the FY2006 strategic document, *Special Nuclear Materials Detection Portfolio: Goals, Objectives, and Requirements*. As defined in that document, the high-level portfolio requirements are:

- Detect shielded highly enriched uranium (HEU);
- Detect SNM at standoff distances; and
- Detect shielded weapon-grade plutonium.

An expert technical and programmatic working group made up of subject matter experts from across the Department of Energy's national laboratory complex was convened to assist in developing this technical roadmap, and was tasked with soliciting input on the current state-of-the-art and important new directions for research relevant to the portfolio requirements. With this input, the working group and the NA-22 staff developed a methodology to organize and analyze the collected data. The result of this effort is a prioritization of R&D topics relevant across the portfolio requirements.

The prioritization, listed in the table on page 10, is the culmination of this effort. The prioritization was obtained from the roadmap process by (a) emphasizing revolutionary over evolutionary approaches, giving greater importance to lower-maturity R&D areas that are likely to produce greater leaps in detection capability, and (b) assigning greater importance to R&D areas that provide the most impact across all three program requirements.

- First-priority R&D comprises technical areas that are currently of lower maturity and offer significant impact across all requirements.
- Second-priority R&D includes technical areas that also are currently of lower maturity and significantly impact at least two requirements.
- Third-priority R&D comprises technical areas that currently exhibit moderate maturity and significantly impact at least two programmatic requirements.

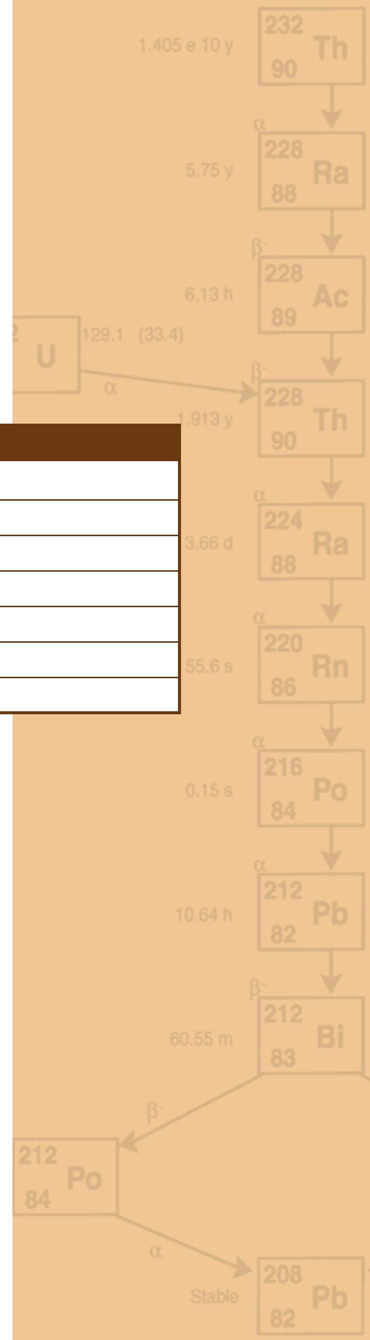
Executive Summary

The prioritization can be generalized in terms of R&D thrust areas that respond to the particular challenges imposed by the portfolio requirements. Active interrogation techniques that exploit either correlated fission signatures or other unique induced nuclear signatures of SNM are an indicated thrust area in detecting shielded HEU. In addition to advancements in sources of interrogating radiation, a systems-level view also emphasizes further development of associated detection technologies, especially those that exploit the identification of correlated signatures from fission. To this end, large-area, high-rate fast neutron detector and high-resolution gamma spectroscopic detector development is identified as a need area. In addition to the important role of active interrogation in providing potential solutions to the standoff and shielded plutonium detection requirements, the impact of both neutron and gamma imaging technologies are also recognized as a high-priority thrust areas. Once again, the role of correlated signature detection is recognized.

Research and development priorities for the SNM Movement Detection Portfolio.

	R&D Technology Area	R&D Technology Class
First Priority	Neutron correlation	Neutron detection—timing, multiplicity, signatures
	Neutron correlation	Large-area detectors—high energy
	Gamma spectroscopy	High-resolution gamma-ray detectors
	Gamma correlation	Gamma detection—timing, multiplicity, signatures
	Neutron source	Accelerator based
	Photon source	Broad spectrum
	Photon source	Monoenergetic
Second Priority	Neutron imaging	3D neutron tracking detector
	Gamma imaging	Electronically collimated system
	Gamma spectroscopy	Algorithms for ID in active systems
	Neutron correlation	Solid-state neutron detectors
Third Priority	Neutron correlation	Large-area detectors—thermal
	Gamma imaging	Mechanically collimated systems
	Neutron imaging	Neutron imaging detectors
	Neutron Source	Radioactive source based

This prioritized requirement list is intended to help guide programmatic decisions for the support of long-term R&D. This list can be used to select topics for proposal solicitations, influence funding decisions for new projects and programs, and to communicate portfolio priorities with the larger nonproliferation community and the laboratory community.



Proliferation Detection Program

The National Nuclear Security Administration's (NNSA's) Office of Nonproliferation Research and Development (NA-22) Proliferation Detection Program (PDP) has established a multi-year strategy in the form of program plans and roadmaps to conduct the research and development (R&D) necessary to demonstrate next-generation special nuclear material* (SNM) movement detection technologies. This strategy sets an aggressive schedule to plan, execute, and demonstrate mission-relevant components and technologies for SNM detection by fiscal year (FY) 2013. The major steps and the schedule for accomplishing the plan are listed in **Table 1**.

Table 1. Program Assessment Rating Tool requirements for the SNM Movement Detection Portfolio.

Year	Activity
2006	Complete general goals, objectives, and requirements
2007	Complete roadmap/program plan
2009	Complete initial technical feasibility studies for alternative technology approaches
2010	Complete external expert/user review and ranking
2011	Complete ranking of alternative approaches and down-selection process
2012	Complete research phase on selected approaches
2013	Demonstrate developed technologies and methods

In 2006, the plan was initiated by convening an expert working group to develop a document that sets the goals, objectives, and requirements for the portfolio. NA-22 published the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements*, NA-22-PDP-03-2006, in FY2006, which defines the requirements for the SNM Movement Detection Portfolio. These requirements form the basis for this long-term proliferation detection R&D program within NA-22. As a next step, NA-22 has undertaken a roadmapping processes to define how the requirements will be met. The resulting roadmap presented in this document will be used to guide the research agenda for the portfolio over the next several years. It is envisioned that several technology paths may be pursued to meet a single requirement; this will be followed by a down-selection to fewer paths to be pursued in more extensive detail. The ultimate goal of this effort is to demonstrate technologies and methods that directly address the portfolio requirements.

* Special nuclear materials are defined by the Atomic Energy Act of 1954 as either "plutonium, uranium enriched in the isotope 233 or the isotope 235, and any other material which the Commission...determines to be special nuclear material, but does not include source material," or "any material artificially enriched in any of the foregoing, but does not include source material. The Nuclear Regulatory Commission (NRC) has the authority to add materials to the list, but thus far has not."

Introduction

The purposes of this roadmap are to:

- Define technology development pathways, both existing and new, for addressing the portfolio requirements.
- Compare technology development pathways, as identified in this document, with currently supported R&D efforts in order to develop a portfolio investment strategy.
- Identify “shortfalls” or technology gaps in pathways that can be used as the basis for future R&D. (Note that shortfalls may be addressed through either R&D and subsequent technology development by NA-22, or by a future “technology insertion” that has been developed externally.)
- Define the guiding principles of a program investment plan for meeting portfolio requirements by FY2013.
- Serve as a communication tool within NA-22 and the larger nonproliferation and research communities.

It should also be noted that the ever-changing nature of the international proliferation situation and the potential for the rapid emergence of new threats, as well as new technological developments, may require that this document be subject to regular revision. The intent is to periodically convene a working group to review the continued relevance of this document and, where necessary, make recommendations for modification.

Purpose of SNM Movement Detection Working Group

In order to better focus the R&D efforts of the SNM Movement Detection Portfolio within NA-22, an expert working group has been assembled to establish a technical roadmap for the SNM Movement Detection Portfolio. This working group consists of technical and programmatic representatives from across the Department of Energy (DOE) laboratory and facility complex. The participating organizations, in alphabetical order, are Argonne National Laboratory, Brookhaven National Laboratory, Idaho National Laboratory, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Sandia National Laboratories, Savannah River National Laboratory, and Y-12 Security Complex.

Overview of NA-22 R&D Program and Boundaries

NA-22 supports R&D projects that encompass developing technology for the early detection of proliferation activity by nations or subnational groups, cooperative and non-cooperative monitoring and analysis of nuclear weapons and materials, and detection of weaponization activities, including monitoring for nuclear testing. NA-22 has two major program elements: the PDP and Nuclear Detonation Detection (NDD) program. The PDP consists of nine R&D portfolios that are grouped by mission areas, enabling technologies, and signatures and observables. The PDP organization is shown in **Figure 1**.

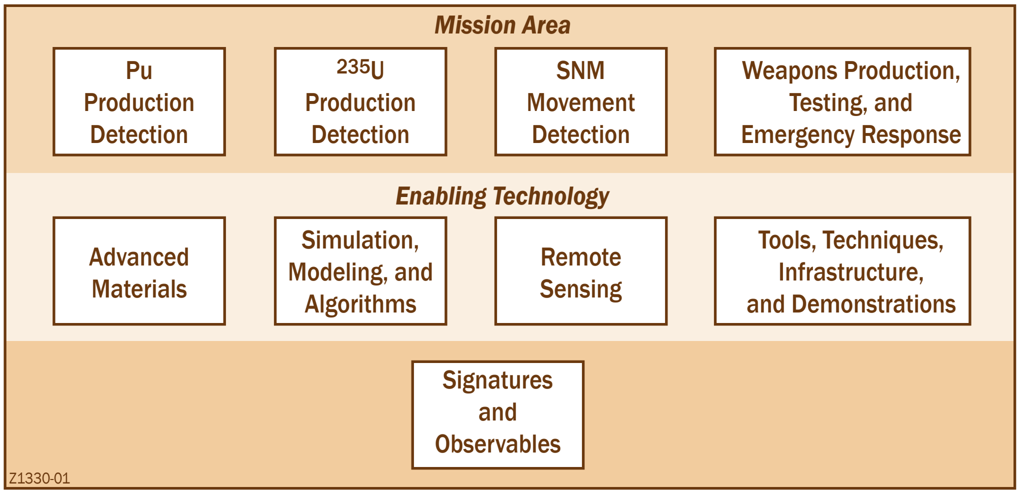


Figure 1. Portfolios within the NA-22 Proliferation Detection Program.

The PDP applies the unique skills and capabilities of the NNSA and DOE national laboratories and facilities to meet the R&D requirements necessary to close technology gaps identified through close interaction with other U.S. government agencies and in support of U.S. government policy. The PDP also draws upon the talents and strengths of the academic community and industry to compliment the national laboratories, where appropriate. The PDP develops the tools, technologies, techniques, and expertise to address the most challenging problems related to detection, localization, and analysis of the global proliferation of weapons of mass destruction, with special emphasis on nuclear weapon technology and the SNM diversion. Additionally, the PDP funds limited research that supports counterproliferation and counterterrorism where there is synergy with the nonproliferation mission.

The PDP plays a key role in filling the critical middle ground between fundamental research and near-term acquisition by using the unique capabilities of the national laboratories to conduct basic and applied research and technology integration. Through the extensive relationships that national laboratories maintain with universities, basic science from academia and federal research programs are brought together to develop real-world system solutions based on classified insights into national security problems. The PDP delivers technical know-how that has been developed and validated to U.S. government acquisition programs and the U.S. industrial base to support national security missions. Technical advances, new proven methodologies, and improvements to capabilities are transferred to operational programs through technical partnerships, including development of special demonstration apparatus to assist major acquisition efforts.

The PDP provides long-term emphasis and support for a broad spectrum of technology areas predominantly considered to be at the applied research and advanced applied research levels of development. In the characterization of technical maturity defined by the Department of Defense (DoD) Research, Development, Test, and Evaluation (RDT&E) Levels, or Technology Readiness Levels (TRLs), this portfolio focuses upon technologies at the RDT&E Level 6.1 and 6.2 or TRL 1–5 (**Figure 2**). These levels of technical maturity correspond to developing a concept, performing basic research, and performing research to demonstrate the proof of principle. In some rare instances, and only after consultation with a specific end user, a technology development project may be taken through a formal demonstration stage of development (TRL 6–7). NA-22 may occasionally provide for field-testing a particular technology, but developing a fieldable demonstration prototype should be in partnership with a specific end user.

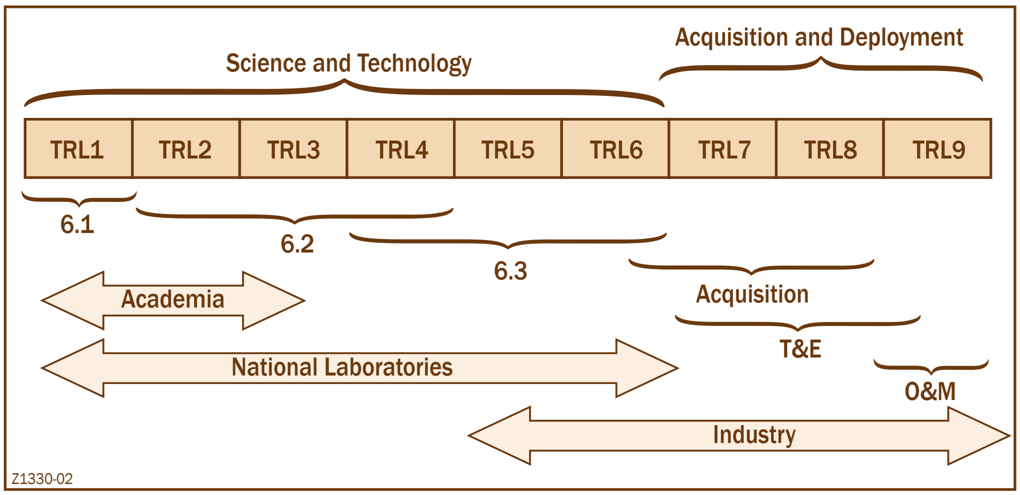


Figure 2. Schematic view of the R&D process from original idea to deployed capability, mapped onto the DoD Research, Development, Test, and Evaluation (RDT&E) Levels (6.1–6.3) and Technology Readiness Levels (TRL 1–9). Both labeling schemes are described in the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document. In general, the PDP manages R&D activity over the RDT&E range of 6.1 to 6.2 or TRL 1 to TRL 6, with most projects being applied research (6.2).

Purpose of the SNM Movement Detection Portfolio

The SNM Movement Detection Portfolio, unique within NA-22, encompasses elements and responsibilities of both a mission-focused portfolio with an embedded enabling technology portfolio. This unique arrangement is defined by the strong coupling of mission and enabling components in developing and employing of radiation detection systems. The portfolio's ensemble of projects spans a continuum from concept development to demonstration prototype. This document, however, focuses on the portfolio's mission aspect. The management details and technology roadmap for the Radiation Sensing R&D portfolio, as well as the related enabling technology portfolio in Advanced Materials, will be covered in a separate document.

This portfolio seeks existing and emerging technologies and techniques that, if further developed, will enhance or enable the end user to detect SNM under their operational requirements. The SNM detection mission space is defined for the purposes of this portfolio as the detection of SNM in threat-relevant forms and quantities in all scenarios outside the boundaries of production and weaponization facilities. The portfolio requires the close coordination and input from a wide range of user and partner organizations, and the other PDP portfolios. The user operational scenarios can range from large emplaced sensor suites for border protection to those intended for clandestine use requiring small, self-contained sensors. Given the large diversity of the user applications and scenarios, it is necessary to distill the user needs into derived requirements that can inform the selection of development activities in this portfolio. The derived user requirements are found below and in the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document.

In contrast to the SNM Movement Detection Portfolio mission, the enabling technology R&D elements, to be addressed in detail, will invest in science and engineering with the potential to significantly enhance the state-of-the-art capability in the detection and identification of radioactive materials unconstrained by end-user detection mission requirements. By focusing on the ability of technologies and techniques to have both high sensitivity and specificity for both SNM and radiological threat materials, the results will be relevant to a large segment of the nuclear proliferation detection community. The enabling technology focus of this element requires close coordination with the entire nuclear proliferation detection community, given the broad applicability of improved radiation sensing capability.

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Portfolio Goals, Objectives, and Requirements

To better focus R&D efforts, the SNM Movement Detection Portfolio has established goals, objectives, and requirements. This set of high-level, user-informed mission requirements provide the target for R&D efforts outlined in this document. In addition, the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document presents the mission and scope of the SNM Movement Detection Portfolio that is required to address ever-evolving proliferation detection challenges.

The primary goal of the SNM Movement Detection Portfolio is to seek existing and emerging technologies and techniques that, if further developed, will enhance or enable the user from the nonproliferation community to detect SNM under their operation requirements. The scope of the SNM Movement Detection mission portfolio is defined as the detection of SNM in threat-relevant forms and quantities in all scenarios outside the boundaries of production and weaponization facilities. Requirements of this portfolio, as influenced by the nonproliferation community end-user needs, are to focus on three high-impact R&D issues—(1) detecting shielded HEU, (2) detecting SNM at standoff distances, and (3) detecting shielded plutonium.

Portfolio Vision Statement

The vision of the SNM Movement Detection Portfolio is to enable enduring technical capabilities to detect SNM worldwide.

Portfolio Mission Statement

The SNM Movement Detection Portfolio addresses nonproliferation community needs by supporting long-term research and development for the detecting movement of SNM.

Portfolio Goals

1. Ensure that the United States maintains global technical preeminence in SNM detection.
2. Develop and demonstrate high-impact technologies for detecting SNM in applications important to the nuclear nonproliferation community.
3. Build an enduring capability for SNM detection by motivating, nurturing, and integrating the best scientific expertise across the science and technology base of the United States.
4. Secure and maintain recognition of the portfolio and its associated scientists and institutions as the principle knowledge base for SNM detection by the nonproliferation community.

Portfolio Goals, Objectives, and Requirements

Portfolio Objectives

1. Develop the most effective technical means to detect SNM consistent with user needs.
   a. Develop radiation sensing technologies that enhance or enable the missions of the proliferation detection community.
   b. Develop alternative and/or complementary technologies that do not rely upon direct radiation detection to enhance or enable the missions of the proliferation detection community.
2. Maintain continual dialogue and coordination with the nonproliferation community to define emerging SNM detection challenges and evolving national security needs.
3. Foster communication, collaboration, and integration among the national laboratories, academia, and industry in developing advanced SNM detection capabilities.
4. Facilitate the transition of technology and exchange of information between end users and the research community.

Portfolio Requirements

The portfolio requirements focus the wide spectrum of possible avenues of R&D investment to high-impact areas of concern common to the largest number of users. These requirements are used in this document to focus the future direction of the portfolio. In a rough priority order, based upon the order of technical difficulty, the portfolio requirements are—

1. **Detect shielded HEU:** Develop technologies that enable detection and/or location of shielded HEU.*
2. **Detect SNM at standoff distances:** Develop technologies that enable the detection, identification, and/or location of SNM at a distance greater than several meters.*
3. **Detect shielded plutonium:** Develop technologies that improve detection, location, identification, and/or characterization of shielded plutonium.*

Portfolio Requirements and the Roadmap Process

The unambiguous detection and characterization of SNM can be incredibly difficult in many scenarios of interest. In the particular case of passively detecting HEU using its intrinsic radioactive signature, its intense but low-energy 186 kiloelectron volt (keV) gamma-ray signature is easily shielded and the spontaneous fission signature is too weak for practical detection. Given sufficiently heavy shielding,

* Material quantities are defined in the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document.

even some active interrogation methods can be rendered useless within the detection time and dose constraints of a particular application scenario. Non-nuclear signatures such as density, shape, and mass are not by themselves indicative of a particular material or threat. Despite decades of effort, there is no magic bullet that will produce a sensor capable of unambiguous detection at arbitrary distances, and there is no appeal from the laws of physics.

Radiation Detection Environments: Detecting SNM in nonproliferation scenarios differs in some important ways from detecting SNM in counterterrorism scenarios, even if there is a large overlap between the sensor and detector technology used to support these different missions. For example, many of the proliferation problems are related to nation states, and SNM movement can occur along a well-defined pathway in a nuclear weapon production complex. An important component is to assist efforts to determine a proliferator's capability and intent, supporting other U.S. and foreign government agencies in an OCONUS* environment. In contrast, the counterterrorism mission is typically characterized by protection at fixed points to define a perimeter defense, and is characterized by the expectation of immediate emergency response action upon detection. From a systems architecture standpoint, these two missions can have vastly different detection architectures, even though they may be supported by very similar sensor and detector technologies. These different architectures and applications have important ramifications for radiation detection systems. At border crossings, for example, a suspect container can be held for further measurements and analysis with relative ease. In contrast, there are no second chances in the covert detection scenario, and those systems must be optimized for a very sparse data set.

An important additional concern influencing technology development is that radiation detection and analysis often does not occur in a vacuum; other supporting technologies may be applied, ranging from analytical technologies (such as information gathering and information analysis) to hardware technologies (such as unattended aerial vehicles and tagging, tracking, locating technologies). Considering the massive investments made in these technologies by other organizations, an appropriate strategy for this program is to apply new developments in supporting areas as they become available rather than invest in the development process itself. These capabilities are especially important in developing SNM detection systems that address particular scenarios of interest. This portfolio will only invest in these areas where necessary to integrate into a capability demonstration.

Standoff SNM: Of the three requirements addressed by the SNM Movement Detection Portfolio, standoff detection is by far the most technically challenging due to the simple fact that radiation intensity per unit area drops as $1/r^2$ from the source, so that the SNM signal-to-background ratio rapidly drops with increasing distance. Enhancing the radiation signal can be accomplished with imaging techniques that concentrate the signal into a selected set of physical coordinates.

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* OCONUS stands for Outside the Continental United States.

While visible light can be focused using lenses to produce an intense spot, imaging gamma radiation requires using either a coded-aperture system that operates on similar principles as a pinhole camera or a Compton imaging system that performs a kinematic reconstruction of a scattering event. These detector systems have been well researched and coded-aperture systems have been commercially produced by at least one vendor. Coded-aperture systems have also been produced for thermal neutron imaging and kinematic reconstruction systems similar to Compton imagers are being studied for fast neutron imaging. It is clear that imaging techniques can deliver improved performance for radiation detection at a distance and are a viable path to improve detection at standoff distances. An additional benefit from imaging systems is that the passive radiographic images can be used to further separate threat objects, expected to be localized, from many naturally radioactive materials, such as granite tiles in which the radiation signature is non-localized and extended.

Given that the direct detection of radiation at a distance is difficult, other alternative signatures have been actively researched. Several signatures have been investigated, and the most promising is remotely measuring induced air ionization. This is accomplished by either directly measuring the ionization in an airstream, in which the plume from a radioactive source is sampled at a distance, or directly measuring the air fluorescence induced by ionizing radiation. Both techniques have been experimentally demonstrated. However, a common feature of these alternative signatures is that they do not directly identify SNM, and the most direct connection to SNM presence is the measurement of the induced ionization. Nonetheless, these alternative signatures are being actively investigated due to the critical importance of radiation detection at a distance.

Shielded HEU: Compared to standoff detection of SNM, detecting shielded HEU is a more straightforward radiation detection and systems integration challenge, although in absolute terms it is extraordinarily challenging. Due to the low intrinsic radiation signature of HEU, reliably detecting shielded HEU will likely require an active detection system in which a neutron or gamma ray, produced by an external means such as an accelerator, is absorbed by a uranium nucleus, which thereby induces a nuclear reaction in the material, the products of which (usually neutrons or gammas) can be more readily detected. These techniques have been successfully and efficiently applied to well-defined problems, such as fissile material control and accounting. Applied to challenging real-world problems such as fissile material detection in a mixed matrix, these techniques are likely the only realistic method for reliably detecting shielded HEU. However, it should be realized that any combination of probe beam and signature can be problematic in a sufficiently large volume. It may be that several modalities will be required for high-confidence detection. For example, a photon beam system might also be used for radiography, enabling some correction for matrix density and composition.

Shielded plutonium: Detecting shielded plutonium is somewhat more achievable than detecting shielded HEU since plutonium has a more significant neutron and gamma-ray signature from its intrinsic decay. While this application relies upon well-developed radiation detection techniques, there are several areas where further development can pay significant dividends. In particular, further development of gamma-ray spectroscopic and neutron detection capabilities will improve the detection of plutonium and significantly improve the characterization of SNM. Here gamma-ray spectroscopy is the leading analysis technique. A key development in this area is radiation detection materials that can be used in room-temperature detectors with resolution performance comparable to cryogenically cooled, high-purity germanium (HPGe). These systems would enable laboratory-quality analysis results in field measurement systems and would furnish a new rapid decision-making capability.

Considering the need to adequately fund development efforts for timely progress, there must be a priority ranking for these development efforts that includes both the ultimate mission need and the consideration of the unique role that NA-22 has in the overall federal national security effort. These recommendations must also include recognition of the mission-relevant R&D programs supported by other agencies and offices, such as Department of Defense's Defense Threat Reduction Agency and the Department of Homeland Security's Domestic Nuclear Detection Office. NA-22 and the other federal agencies that sponsor R&D in the areas of radiation detection and radiation detection material science have formed the Interagency Radiation and Nuclear Detection Working Group, whose purpose is to coordinate R&D efforts across the interagency. This working group is sanctioned under a memorandum of understanding among the agencies listed above and the Office of the Director of National Intelligence. The SNM Movement Detection Portfolio has a demonstrated history of co-funding or coordinating funding in areas of mutual interest amongst federal agency missions in order to accelerate the development of new national capabilities.

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Concepts of Operations Summary

The SNM Movement Detection Portfolio seeks to serve the interests of a wide array of nonproliferation users by conducting R&D that leads to new capabilities. The complexity and variety of user Concepts of Operations (ConOps) in the nonproliferation community presents a significant challenge developing a comprehensive strategy for relevant R&D. With such breadth in user operations, for practical reasons it is necessary to consolidate individual user needs into common requirements that can be easily communicated with the R&D community. The process is conducted under the insistence that these must result in new capabilities for the broadest possible range of nonproliferation users.

The *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document contains complete details* on eight mission scenarios that span the broad application space of the nonproliferation community. These scenarios range from cooperative to non-cooperative and include users from multiple U.S. government agencies and departments.

Derived Common User Requirements

As noted in the previous section, the user community served by this portfolio is very diverse. NA-22 has long-standing relationships with a broad array of end users and partner organization interested in SNM detection. Since each user is constrained by different scenarios and ConOps, the technological solutions to these questions can differ widely between users. For example, the physical parameters of the system, sensitivity, operational lifetime, complexity, ease-of-use, and form-factor can vary widely between two users operating nominally similar systems. It is the inevitable conflict between the requirements imposed by the mission needs and the constraints imposed by the ConOps that drives the technology development process. Therefore, it is necessary for NA-22 to derive a set of common user requirements for SNM detection systems based on our understanding of each user's needs. This set of derived user requirements is critical in the early phase of technology development and concept evaluation given that most users choose not to be involved in such early phase development, and more importantly many users are reluctant to give operational details to the broader research community.

The following derived user requirements represent the general needs of the users identified in the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document. In broad terms, the overarching requirements can be simply described as:

- Detect: Is SNM present?
- Locate: Where is the SNM? What is the spatial distribution?

* See the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document for complete mission scenario details.

Concepts of Operations Summary

- Identify: What is the isotopic composition of the detected SNM?
- Characterize: What is the mass and composition of the SNM? How much is present and in what form?

Building upon these overarching and general questions, together with the user needs across the nonproliferation community, the specific focus areas to be addressed by the SNM Movement Detection Portfolio are summarized in the following paragraphs. These derived users requirements result from applying specific user ConOps to the four principal detection questions above. This list is in priority order based on current technical capability and user need.

1. **Detect:** Detect bare and shielded SNM post production, including weaponization, but prior to its ultimate use, in quantities of interest for smuggling* or larger, and discriminate from non-SNM materials in choke point (border crossing) screening, perimeter detection, and standoff interrogation.
2. **Identify:** Identify and in some cases also quantify bare and shielded SNM, once detected, in trace* amounts or larger, for both man-portable and laboratory detection systems.
3. **Locate:** Detect, locate, and in some cases identify bare and shielded SNM post production and/or weaponization, but prior to ultimate use, in quantities of interest for smuggling* or larger, in detection systems for use in man-portable search systems, and vehicle-mounted (air, sea, and land) systems.
4. **Characterize:** Determine spatial distribution and in some cases identify SNM in a volume of interest, in quantities of interest for smuggling* or larger, for man-portable, transportable, and laboratory detection systems.

Generalized ConOps for Roadmap Process

The four derived user requirements from the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document are further refined for the purposes of the technical roadmap process. The working group found it useful to define three broad ConOp categories that respond to these derived user requirements, namely Search, Contain/Screen, and Characterize. Generalized ConOps were selected such that they span the broadest range of nonproliferation user community missions, and highlight the important constraints on systems imposed by the manner of use. There are four principle issues considered for each ConOp: (1) user access to and control of the object, (2) relative motion of the sensor (both to earth and object), (3) observation time, and (4) required transportability. These general ConOps are then used as constraints when considering the current technical solutions and the potential R&D paths to new capabilities for the mission requirements.

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* See the *Special Nuclear Material Detection Portfolio—Goals, Objectives, and Requirements* document for definitions of threat, smuggling, and trace quantities.

The **Search** category is defined, for the purposes of this document, as the deployment of an SNM detection capability to a defined search region with the intent of uncovering previously undetected SNM. This generalized ConOp embodies aspects of the Detect, Identify, and Locate derived user requirements. For many users a search activity can be characterized by a moving sensor platform that is attempting to detect a threat over a defined search area. The threat object can be stationary or in motion. This ConOp imposes significant difficulties on the detection because of the dynamic background introduced when a sensor system is in motion. Another significant constraint on search systems is the requirement that the system be transported to the search area and often carried and operated by a single person. Such systems have specific characteristics (e.g., robustness, low power consumption, low weight).

The primary element of any search operation is the detection of the defined threat object, SNM in our case. It is also imperative that the threat object be located. This is followed in some user ConOps with a need to Identify the object to positively identify it as SNM or a particular isotopic form of SNM. Once the material has been located, some users will then need to characterize the material as described below.

The **Contain/Screen** category is defined, for the purposes of this document, as the deployment of an SNM detection capability to detect the movement of SNM as it transits in or out of a defined boundary. This generalized ConOp embodies aspects of the Detect and Identify derived user requirements. Containing SNM inside a boundary is relevant to a host of actual user situations ranging from border protection to material accountancy and protection. The typical situation involves stationary detectors that cover a defined border or boundary, i.e., defined entry and exit points. The stationary nature of the typical system often reduces background fluctuations, which reduces total uncertainty in measurements. Because such systems are many times permanent and supported by local infrastructure, they can often be larger and consume more resources than search tools. There are notable exceptions, however, with unique constraints similar to that described above for Search. In this ConOp, total time of observation for an item or group of items may be short and outside the control of the user. The primary function of the Contain/Screen ConOp is to detect the defined SNM threat. In some user ConOps, it is also necessary that the system Identify the threat object, typically with isotopic means. This identification is utilized to reduce false or nuisance alarms caused by non-SNM radioactive materials.

The **Characterize** category is defined, for the purposes of this document, as the development of an SNM detection capability that can determine the spatial, physical, and chemical properties of SNM. This generalized ConOp is wholly described in the Characterize derived user requirement. Currently for many users this ConOp is indicative of situations where the user has control over the object and often has significant time for evaluation. Backgrounds are often controlled and systems are stationary and have significant resources available. This ConOp includes situations that range from field inspection of a suspect object to laboratory analysis of a sample.

Concepts of Operations Summary

For the purposes of this document, the program requirements to detect shielded HEU and shielded plutonium are constrained to a range of less than three meters. The standoff requirement includes all cases where SNM, shielded and unshielded, needs to be detected at distances greater than three meters. These definitions are useful to frame the discussion and to delineate between technologies and techniques applicable for close- and extended-range detection. There is no community-wide accepted definition for standoff, although it is recognized by many in the community that standoff range is considered to be on the order of tens of meters, consistent with the current document.

Examples for each of the generalized ConOps categories within each program requirement were adopted by the working group during the roadmap development process to help illuminate the particular constraints imposed. These examples are in most cases technologically very challenging to help force the group to consider novel solutions.

Requirement 1: Detect Shielded Highly Enriched Uranium

Research and development that will lead to demonstrating new capabilities for detecting shielded HEU is the highest priority of the SNM Movement Detection portfolio. Shielded HEU detection represents a very significant challenge in the portfolio due to the nature and paucity of natural radioactive emissions from HEU. These emissions are often easily shielded and are influenced by the provenance of the source material. The fact that passive signatures from HEU may be practically nonexistent in many shielding configurations possible in ConOps of interest requires a more aggressive approach. The approach focused on in this document is stimulating the uranium nucleus by probing the object with an external radiation source and observing the characteristic return signature. The challenge is to develop new interrogation systems that incorporate this stimulant, and observation methods in a form that can be applied to the relevant ConOps.

Representative Shielded HEU Search Example

- Board a ship at sea and search unstructured, noncontainerized cargo below deck.

This example requires small, person-portable, robust, waterproof, low-dose, low-power, and short decision-time systems. A system in this hypothetical ConOp would be person carried on board a ship for inspecting the ship and cargo.

Representative Shielded HEU Contain/Screen Example

- Unattended active system monitoring transport in/out of a facility of interest:.

This example requires low-power, small, portable, low-dose, short decision-time systems that also need to communicate results and require low-probability intercept and low-probability detection communication protocols.

Representative Shielded HEU Characterize Example

- Country X opens up for declaration verification.

This example requires a quantitative method for determining mass, isotopics, chemical form, and package characterization. Systems will need to be robust and meet the constraints of the particular declaration agreement.

The common goal for all examples is to detect and identify shielded HEU threats in weapon forms or as bulk material from a distance less than three meters. The primary long-range observables from all fissile materials such as HEU and plutonium are gamma rays and neutrons, which have mean free paths of the order of a hundred meters in air and only 10 cm in water. However, because spontaneous fission in HEU produces fission spectrum neutrons at a fairly low rate of about between 2 and 11 per second per kilogram, depending on the level of enrichment, it is not possible to use this observable alone to detect HEU above background activity. Therefore, passive methods of detecting of shielded HEU rely on detecting characteristic gamma rays. Because the observable gamma emissions of the various isotopes that may be present in enriched uranium vary substantially in both energy and activity, it is necessary to consider the conditions under which passive detection might be an acceptable detection means. In situations other than in the special cases described below, active methods will be required.

Detecting Shielded HEU in Special Cases

Materials used to shield the HEU can substantially attenuate the emitted gamma rays, thereby reducing the effectiveness of gamma ray-based detection systems. Furthermore, the gamma-ray activities and energies from various uranium isotopes vary substantially. Because the HEU composition will determine the composite spectrum emitted, it is useful to consider both shielding and isotopics in examining potential detection approaches using gamma rays as indicators. While we assume no a priori knowledge of the configuration of shielded HEU, it is nevertheless useful to analyze various configurations to assess the most promising detection technologies.

Highly enriched uranium is considered a threat because it contains a large fraction of the fissile isotope ^{235}U. The spontaneous gamma emissions from ^{235}U occur predominantly at low energies, although the activity at 186 keV is relatively high. In the case that the shielding of the HEU is insufficient to completely extinguish this gamma-ray emission, passive gamma-ray sensing with spectroscopic information could allow detection, location, and characterization ability of the material. These technologies are evaluated in the Requirement 3: Detect Shielded Plutonium section (on page 31).

If the shielding has sufficient stopping power (high Z and thickness) to eliminate the gamma rays characteristic of ^{235}U, it may be possible to detect the shielded

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HEU by observing gammas from other isotopes of uranium present in the material. HEU derived from reprocessing fuel from a plutonium production or power reactor will contain ^{232}U and its decay products, with ^{208}Tl having a characteristic gamma at 2,614 keV. This high-energy gamma ray will be highly penetrating and difficult to shield completely. Furthermore, because of the high activity, the presence of even small amounts of ^{232}U will permit detection of the material over reasonable time frames. In these situations, the ^{232}U gamma rays observed will allow the detection of even substantially shielded HEU using passive gamma-ray detection technologies required for satisfying Requirement 3: Detect Shielded Plutonium.

The gamma emission from the ^{238}U decay chain can also be a useful signature. Comparing the most useful gamma rays in these two decay chains, the 2,614 keV gamma ray from the ^{232}U daughter ^{208}Tl and the 1,001 keV gamma ray from the ^{238}U daughter ^{234m}Pa, the intensity of the 1,001 keV line is about 7% of the 2,614 keV line in HEU that has a 100 ppt ^{232}U concentration that is typical of the HEU produced in programs with extensive uranium recycling. However, for an equal mass of HEU and either depleted uranium* (DU) or natural uranium, the 1,001 keV emission from DU is the same as the 2,614 keV emission from HEU. This signature could be relevant to scenarios in which depleted or natural uranium with nearly 100% ^{238}U content is used to shield HEU. Therefore, if the shielding consists of DU, or if the HEU is lightly shielded with another materials, it may be possible to passively observe the characteristic ^{238}U gamma emissions, e.g., at 1,001 keV, in order to indirectly detect the shielded HEU. As mentioned above, these technologies are described in the Requirement 3: Detect Shielded Plutonium section (page 31).

Shielded HEU Detection in Difficult Cases

In situations where the HEU isotopic composition and/or shielding configuration does not fall into the special cases described above, it will be necessary to enhance the signal-to-noise ratio to permit high-confidence determinations. One promising approach (among many that include fission, NRF, etc.) to extract a unique HEU signature is to actively stimulate the ^{235}U nucleus to induce fission and observe the resulting release of energy, usually in the form of neutrons and gamma rays. These emissions must be stimulated in a manner that also minimizes “induced noise” signals associated with activation of or scattering by intervening material or shielding. Because the temporal and spectral characteristics of the released energy vary depending on the form of the interrogation energy, this roadmap considers source technologies capable of stimulating fission in ^{235}U, as well as detection technologies capable of measuring the prompt or delayed energy. Because interrogation sources must be used in conjunction with appropriate detectors, the analysis considers both sources and detectors in system contexts. For example, to avoid saturation, detectors might require the ability to time synchronize with a source pulse to reduce obscuring induced background radiation.

* Depleted uranium is defined as uranium with lower than natural enrichment of ^{235}U, or > 99.3% ^{238}U.

Requirement 2: Detect SNM at Standoff Distance

As defined in this document, the standoff detection requirement encompasses all remaining scenarios that seek to detect SNM, in all forms, in all shielding configurations, at distances greater than three meters. This inclusive requirement is intended to cover the broad needs of the nonproliferation community in the areas of detecting, identifying, localizing, and characterizing SNM. It is recognized that the defined standoff range of greater than three meters poses varying levels of difficulty under ConOps considered. The selection is not entirely arbitrary and is loosely based on current operational conditions. Given that all users wish to extend the current range of detection capabilities to ever greater distances, this requirement focuses on technologies that have the potential to extend that range. These include passive imaging technologies and the exploitation of unique stimulated signatures.

Representative Standoff (> 3 m) Search Example

- Detect SNM in a vessel on the high seas from a platform at standoff distances.

This example requires detection capabilities at distances of at least tens of meters, ability to detect through hull material and cargo, detect material below the water line, low dose to operators, and a robust fieldable system that is optimized for the maritime environment.

Representative Standoff (> 3 m) Contain/Screen Example

- Detect SNM in a truck moving between inaccessible facilities in a country of interest.

This example requires detection of material at stand off distances from a few to tens of meters, detection through cargo and intentional shielding, low probability of intercept/low probability of detection (of emplaced sensor system), and potentially low power.

Representative Standoff (> 3 m) Characterize Example

- Characterize UF_6 cylinders in transit at standoff distances.

This example requires detection capability at may tens of meters, ability to positively identify material, quantitative methods for determining mass and isotopics, low dose to operators, and a robust fieldable system.

The standoff detection of SNM requirement focuses on R&D necessary to detect all SNM, as defined in the *Special Nuclear Materials Detection Portfolio: Goals, Objectives, and Requirements* document, in all forms and quantities applicable to the nonproliferation community. As distance between the threat and detector increases, the difficulty to detect passive radiation signatures also increases. As

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discussed above, and in detail in the *Special Nuclear Materials Detection Portfolio: Goals, Objectives, and Requirements* document, SNM threats all emit neutrons and gamma rays of varying energies and intensities. In general, the more intense and more energetic the emitted radiation, the more readily detectable it is at increasing distances. As distance from the threat increases, two independent factors reduce the total intensity of the signal. For isotropic sources of radiation (those that emit equally in all directions) a geometric reduction that varies as the reciprocal of the distance squared, $1/r^2$, reduces the radiation per unit detection area. This factor is energy- and species-independent and has a significant effect on detectability as distance increases. The second factor is the absorption or scattering of emitted radiation in the intervening material between the detector and the threat. For gamma and x rays, this factor is dependent on the energy of the emitted radiation and the charge, Z, of the constituent intervening material elements. For neutrons, this factor is largely dependent on emitted energy and the hydrogen content of the intervening material. These two factors, along with the local operating environment's radiation background, impose physical limits on the detectability of a threat.

Despite the above-mentioned difficulties with passive radiation detection at standoff distances, these techniques can still be viable in certain situations. The use of large-area detectors and, particularly, large-area imaging detectors, increases the effectiveness of detection at distance. Imaging detectors both locate threats in the detector field of view and increase the overall sensitivity for threats, due to the rejection of interfering background radiation from surroundings not in the field of view that plague non-imaging large-area detectors.

When SNM is at a distance or is shielded sufficiently to reduce the passively emitted radiation below a level that is detectable, the signature can be enhanced by stimulating radiation emission. In these so-called "active interrogation" methods, a source of radiation is used to excite nuclear or atomic states or induce fission and promote emission of radiation that is more detectable. This stimulated emission may be both more intense and of different species or energy than that emitted passively by the material. One example is the induction of fission in SNM by stimulation with high-energy photons. This interaction enhances the natural spontaneous fission signature by promoting fission at a rate that is proportional to the intensity of the interrogating beam of photons. These techniques offer the potential for SNM detection at distances from hundreds to thousands of meters.

Regardless of the interrogating particle, active inspection relies on stimulating some sort of reaction in the item of interest, which will cause the emission of a signal that can be detected and analyzed. For SNM, the fact that the material readily fissions when stimulated by neutrons or gamma rays, with energy greater than the photofission threshold, allows the prompt and delayed fission products to be monitored to indicate the presence of SNM. When an isotope such as ^{235}U or ^{239}Pu undergoes fission, emitted radiation will be in the form of both prompt and delayed neutrons, and photons. The fission process immediately liberates energetic gammas and neutrons within $< 10^{-14}$ seconds after interaction with the stimulating source radiation. Prompt emissions also occur after the interrogating pulses from fissions induced by delayed neutrons slowing down to thermal energies. Both neutron and photon emissions are produced with a spectrum of energies but in discrete numbers: typically, 0–6 neutrons, 0–20 photons. On average, however, roughly 2.42 neutrons and 7 photons are emitted from the thermal neutron fission of ^{235}U. Yields from photofissions of materials such as ^{235}U and ^{239}Pu are of similar magnitudes. Delayed neutrons and photons will also be emitted from the neutron-rich daughters and unstable fission products. These delayed products, which are emitted on time scales of milliseconds to several seconds after the fission process, are much less abundant than the prompt emission. On average, only 0.0158 delayed neutrons are emitted from thermal ^{235}U fission; at higher interrogation energies, the ratio of prompt-to-delayed neutrons increases.

In addition to the passive and active signatures discussed above, there may be other SNM signatures that do not rely on radioactive SNM emissions for detection. Techniques for detecting these alternate signatures include sensing either (1) secondary radiation signatures that are created by the interactions of the primary passive SNM radiation emissions, or (2) those that are completely independent of the SNM radiation emission. Thus far, investigation into these techniques has shown them to be elusive at best and of only limited applicability to SNM detection. There is a recognized need for continued research into new exploitable alternate secondary and non-radiometric signatures of SNM that offer ease of detection through shielding and at standoff distances.

Requirement 3: Detect Shielded Plutonium

Detecting shielded plutonium completes the highest-level requirements for the SNM Detection portfolio. Due to the nature of the spontaneous radiation emissions from plutonium, it is more difficult to shield than HEU. This characteristic radiation is, in general terms, more penetrating and more abundant than that from HEU, making passive techniques more applicable for most ConOps. As well, the stimulated or active techniques explored in the shielded HEU section are expected to be directly applicable to shielded plutonium detection. The goal for the entire example ConOps is to detect, locate, identify, and characterize shielded plutonium in weapon or weaponizable forms, and relevant chemical compositions. Applications that require detecting shielded plutonium include, but are not limited to:

Representative Shielded Plutonium Search Example

- Detect shielded plutonium on an airplane during flight.

This example requires large-area detection capability and a system that can withstand the rigors of flight environments. In an airborne detection system, the background will change dramatically with altitude.

Representative Shielded Plutonium Contain/Screen Example

- Unattended passive system monitoring transport in and out of a facility of interest.

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This example requires large-area detectors and automated algorithms for analyzing and interpreting data in addition to being potentially low power and robust. These systems may be additionally constrained by communication protocols that impose low-probability intercept and low-probability detection.

Representative Shielded Plutonium Characterize Example

- Country X opens up nuclear fuel storage facility for access.

This example requires a detection system that provides a passive, quantitative method for determining mass, isotopics, and chemical form of material inventory.

The shielded plutonium requirement focuses on research and development paths relevant to detection of smuggling and threat quantities of plutonium, with shielding ranging from moderate, or 50% attenuation, to heavy, or > 99% attenuation of the emitted gamma or neutron radiation. Because long-range standoff detection of SNM is a separate requirement in this roadmap, we fix the standoff distances for detection of shielded plutonium to be less than three meters—defined earlier as near to intermediate range.

For near- to intermediate-range detection, most applications involve exploiting the penetrating gamma rays and neutrons emitted by plutonium. Unshielded plutonium has a relatively robust gamma and neutron signature compared to unshielded HEU. It is this distinction that motivates our separate treatment of plutonium detection methods in this section of the roadmap. In approximate terms, weapon-grade plutonium emits some 60,000 neutrons per kilogram per second, while HEU emits less than 1 neutron per kilogram per second. The characteristic gamma energies emitted by plutonium are somewhat higher energy, and therefore more penetrating than those of HEU. For weapon-grade plutonium, these range from 300–900 keV, compared to a 186 keV for the principal gamma-ray line emitted by HEU. Both factors make plutonium somewhat easier to detect than HEU, and imply that active interrogation methods are less likely to be needed to monitor or discover shielded threat quantities of plutonium at standoff distances of three meters or less. That said, even at this standoff distance there are shielding configurations in which plutonium materials can be practically invisible to passive detectors, particularly when the constraint of limited dwell time is imposed, as is often the case in practical situations. In this document, we focus primarily on passive detection methods for this requirement; techniques involving interrogating beams are covered in detail in the Requirement 1: Detect Shielded Highly Enriched Uranium section (page 26). It is expected that active interrogation technologies and techniques developed for detecting shielded HEU will have direct applicability to detecting shielded plutonium with little or minor modification.

Technology Overview: Current State of the Art

Although there are many excellent techniques to detect and characterize SNM in controlled settings, the technologies relevant to the potentially unconstrained nuclear nonproliferation environment must be appropriate for detecting a variety of materials shielded and masked by a capable adversary. There is a premium placed upon techniques that are highly specific to SNM and can penetrate significant amounts of shielding. The most unique and relevant signature of SNM is fission, with fission occurring either as a natural decay process of the SNM (spontaneous fission, a *passive* signature) or as an induced reaction during active interrogation with neutron or gamma-ray beams (induced fission, an *active* signature). A further advantage of the fission signature is that the correlated emission of neutrons and gamma rays allows a variety of background-suppression techniques using coincident neutron and gamma-ray counting. Gamma-ray spectroscopy is also a unique signature of a particular isotope and it is especially relevant for SNM characterization, but its applicability for passive SNM detection can be limited for some materials, such as HEU, where the decay gamma rays are easily shielded (as discussed in Requirement 3: Detect Shielde Plutonium). Nuclear resonance fluorescence (NRF) is an active detection method in which a gamma-ray beam is used to induce a gamma-ray signature in materials; in the case of HEU, the strong NRF transition at 1,733 keV is much more penetrating than the 186 keV gamma ray emitted during the passive natural decay of HEU. Nearly all SNM detection and characterization relies upon the detection of either or both neutrons and gamma rays due to the combination of penetrating radiation and material characterization.

The development of other techniques for SNM detection continues to be a priority, however, since the conventional techniques are difficult to apply at large standoff distances due to the lack of practical options for focusing gamma rays and fission neutrons. There are active research programs in detecting radiation using induced secondary effects, including ionization and excitation of air. One feature of nearly all alternative signatures is that relying upon the secondary signatures (such as ionization and excitations) removes the SNM specificity and characterization of direct nuclear radiation detection (i.e., these techniques can only be used to detect radiation without attributing it to a particular isotope.

There is an important class of other, ancillary technologies that are useful in the context of a SNM detection system. Chief among these is radiography, since adding more shielding to suppress the nuclear radiation signature directly increases the radiographic signature. Tagging, tracking, and locating methods can be used to cue radiation detection assets to a suspect person, vehicle, or facility. Adding radiation detection equipment to unmanned aerial vehicles offers the possibility of access to denied space. Considering that there is substantial investment in these technologies by other federal offices and programs, however, these technologies will not be developed within the SNM Movement Detection Portfolio. If it is later discovered that there is an unsupported nonproliferation niche for which incremental investment would provide significant impact, funding support may be considered in these areas.

Technology Overview: Current State of the Art

The three requirements of the SNM Movement Detection Portfolio are to detect shielded HEU, detect SNM at standoff distances, and detect shielded plutonium. Given these requirements and the recognized need to detect SNM signatures that result from their unique radioactive properties, the organization of techniques and technologies is defined around those exploitable signatures of SNM. To that end, the process identified nine general technical areas that span the technology space relevant to this effort. In addition there were identified twenty subcategories or technology classes to further refine the discussion. These technology areas and classes are as shown in **Table 2**.

Table 2. R&D technical areas and classes used in this document.

R&D Technical Area	R&D Technology Class
Gamma correlation	High-rate, high-multiplicity gamma detector
Gamma imaging	Distributed sensor systems
	Electronically collimated system
	Mechanically collimated systems
Gamma spectroscopy	Algorithms for ID in active systems
	High-resolution gamma-ray detectors
Neutron correlation	Alternate neutron detectors
	Large-area detectors—high energy
	Large-area detectors—thermal
	Solid-state neutron detectors
	Timing and multiplicity
Neutron imaging	3D neutron tracking detector
	Neutron imaging detectors
Neutron spectroscopy	Ultra high-resolution neutron spectrometry
	Neutron spectroscopy systems
Photon sources	Broad spectrum
	Monoenergetic
Neutron sources	Accelerator based
	Radioactive source based
Other sources	Muon sources, proton sources, ...

There are some important commonalities between the technical areas that should be noted, in particular, correlated gamma-ray and neutron detection should be considered in the context of both being related to the detection of penetrating radiation from nuclear fission.

Correlation counting refers to the detection of neutrons and gamma rays emitted in coincidence during the fission process. Approximately seven to ten gamma rays with average energy 1 MeV and one to eight neutrons with average energy 2 MeV are emitted during fission. ***Gamma-ray correlation*** refers to gamma-ray counting with additional timing, coincidence, or multiplicity information data, while ***neutron correlation*** refers to the same general technique of neutron counting with additional timing, coincidence, or multiplicity information data. There also exists a combined mode for detecting both gamma rays and neutrons simultaneously. This subject is adequately discussed in the context of individual particle correlations and will not be discussed separately. The key research issues associated with correlation counting physics are further investigation of “long chain” events in which there are multiple fission events due to neutron self absorption within the SNM and the ability to extract these events using timing or coincidence information. The key technology issues are the development of counting systems for active interrogation systems. In an active interrogation system, the detectors must be (a) operable within the timing structure of the accelerator in a pulsed system, (b) capable of tolerating the data collection rate in a steady-state system, and (c) scalable to a large area for active interrogation at standoff distances. For passive detection of plutonium, some of these requirements can be relaxed due to the lower overall count rate, while other requirements (such as scalability) continue to be important.

Imaging requires the use of techniques to reconstruct and localize the position of the emitting source, resulting in background reduction and improved signal-to-noise characteristics. The most relevant application will be standoff detection of SNM. While the most common interpretation is using kinematic reconstruction in coded-aperture or Compton scatter cameras, another possibility is using multiple sensors to track or locate a source, then correlating the sensor responses to improve the signal to noise. There are both ***gamma imaging*** and ***neutron imaging*** technologies developed for applications other than SNM detection. The National Aeronautics and Space Administration (NASA) has been very active in this field and has flown several gamma-ray imaging systems. Coded-aperture cameras have been built for both gamma-ray and neutron imaging, with the majority of neutron coded-aperture cameras being constructed for thermal neutron imaging. The research challenges for gamma-ray imaging are concentrated in the areas of Compton imaging with high energy-resolution detectors suited for both detection and characterization. Fast neutron imaging is not at a comparable state of development, and the first generation of instruments is only now being built using kinematic reconstruction of a multiply scattered neutron’s trajectory to reconstruct its incident direction. Distributed sensor systems can be viewed as a subset of imaging, and the research challenge is at both the overall system and individual sensor level. At the system level, for example, optimizing the distribution of sensors to achieve the best probability of detection will be a challenge, while sensor-level challenges include balancing detection capability against sensor size and power requirements.

Spectroscopy refers to measuring the energy distribution of the subject particle species. The gamma-ray emission spectrum of SNM consists primarily of monoenergetic gamma rays, with the best examples being the 186 keV gamma ray from HEU decay and the 375 and 414 keV gamma rays emitted during ^{239}Pu decay. ***Gamma spectroscopy*** enhances the signal-to-noise ratio by (1) excluding all background not in the energy region of the characteristic gamma ray and (2) reducing the overlap between adjacent peaks. Gamma spectroscopy is the single most useful tool for detecting and characterizing radioactive material. There are three broad classes of detectors for gamma spectroscopy: small-volume, cryogenically cooled, HPGe detectors with high-resolution; medium-volume, inorganic scintillators with medium resolution, such as sodium iodide; and large-volume, plastic scintillators with poor energy resolution. While better analysis algorithms may someday significantly improve performance for materials such as scintillators, moving the analytical capability of a HPGe system to the field will require a significant R&D program to develop new materials.

Neutron spectroscopy has thus far not been developed to the same extent as gamma-ray spectroscopy for two reasons. First, the neutron energy distribution from fission is a broad continuum largely devoid of distinguishing features. Neutron spectroscopy can distinguish between fission neutrons and those from (α,n) reactions, however, and neutron spectroscopy is particularly valuable in characterizing the matrix around a neutron emitter. Second, fieldable high-resolution neutron spectroscopy is a somewhat new technique. It may indeed be useful in fully characterizing the neutron emission from complex samples such as SNM mixed with a light element, resulting in a combined fission and (α,n) spectrum.

Photon sources refer to accelerators used to produce high-energy x rays that in turn can be used to induce photofission, NRF, and other gamma-induced reactions in SNM. Photofission in SNM requires gamma rays of 6 MeV or higher energy and, in general, most photofission systems tend to operate with a pulsed accelerator source. NRF, on the other hand, is expected to require a steady beam for best interrogation results. The utility of pulsed sources for NRF is a subject of current investigation. There is a need to produce sources optimized for these applications because most existing photon sources are based on industrial linear accelerators produced for radiographic applications. A particularly appealing source for NRF may be a laser backscatter/Compton backscatter system. These sources could be tuned to produce gamma rays in a narrow energy range around a single energy for a particular NRF signature. This type of accelerator could have a much lower dose than a broad spectrum bremsstrahlung system, depending on the application (e.g., proximity, interrogation time, intensity). An additional exciting feature of many photon sources is that in addition to inducing nuclear reactions like photofission and NRF, they may also be used for radiography, an important ancillary data set to detect the presence of heavy shielding. Defining the requirements for these beams requires more R&D in active interrogation systems.

Neutron sources broadly refer to accelerator- and isotope-based methods for producing neutrons for active interrogation. Compared to photon sources produced for the industrial radiography market, there has been much less industrial participation in the area of neutron source development. Unlike photofission, neutron-induced fission can be accomplished at any energy in SNM, including very slow or thermal neutrons. This enables several different types of active interrogation systems to be considered. Some neutron sources could be relatively simple ion source-based generators operating on the deuterium-deuterium or deuterium-tritium reactions, photoneutron sources with deuterium, or higher-energy particle accelerator approaches based upon proton- or deuteron-induced reactions. There is also a subclass of isotope-based sources that use spontaneous neutron emitters (such as californium) or alpha particle-induced, neutron-producing sources with an actinide/beryllium mixture. These sources may have an important role in lightweight systems for field use. Defining the requirements for these beams requires more research and development in active interrogation systems.

Other sources include new concepts such as muon beams, high-energy proton beams, antiproton beams, and other advanced beams. For the most part, these sources support detection at a distance. These concepts are being actively explored in the interagency R&D community, but have not yet progressed to the point that source requirements can be written.

In **Appendix A**, we provide an overview of each technology area, along with examples of currently available systems, current R&D efforts, and shortfalls.

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Technology Assessments by Requirement

The SNM Movement Detection working group conducted a survey of the R&D activities across the DOE national laboratory and facility community to ascertain the current state of the art in SNM detection and identify promising avenues for further research. This survey information comprised the launching point for the working group experts to access the R&D approaches to SNM detection for each of the three portfolio requirements. From this information, the working group identified nine broad technology areas and twenty technology class categories that span the SNM detection R&D landscape (Table 2). Each technology class was assessed by portfolio requirement per generalized ConOp in each of eight parameters that include: shortfalls for passive detection, shortfalls for active interrogation, maturity in state of technology development, technical risk, impact to the program objectives, cost of development, time to develop to demonstration, and requirements for underlying enabling technology development. The results of these assessments are provided in **Appendices B, C,** and **D**.

The shortfalls listed in the Tables B1, C1, and D1 list the most significant technical gaps in each subtechnology area for a particular portfolio requirement and generalized ConOp. Since it is recognized that substantive differences appear in passive vs. active interrogation modalities, the shortfalls are listed separately for those that (a) are encountered in passive detection systems and (b) would likely be encountered in an active system that utilizes an external radiation source to stimulate a particular signature. The information in these sections captures the needs or requirements of the particular technology when considered only within the generalized ConOp for a specific portfolio requirement, and includes details of needs or requirements for that technology class when mature.

The enabling technology category in Appendices B, C, and D is intended to provide substantive input to the enabling technology R&D portfolios within NA-22 and the broader support community regarding the needs of the SNM Movement Detection mission portfolio for new enabling technical capabilities. To achieve the full capability envisioned for a particular technology area, the required enabling technology must mature sufficiently for integration into the envisioned mission portfolio solution. This need introduces a significant element of uncertainty in the time and cost for a particular technology development path and its applicability to the SNM detection mission. As such, this input is provided to the enabling portfolios within NA-22 as formal requirements that support the SNM Movement Detection mission.

The cost associated with R&D efforts to develop a particular technical area to a demonstration capability that address specific mission requirements was also assessed by the working group. The dollar figures provided are considered gross estimates only and were arrived at by the working group in a process completely unconstrained by and disassociated from the federal budget process. The dollar figures provided in the data tables assume level funding for each anticipated development year in FY2007 dollars, and thereby do not account for inflation or other cost escalations influencing the total effort to execute R&D at the national laboratories and facilities. In developing these estimates, there was no rigorous evaluation of cost conducted for a particular technology development path. Rather, a consensus estimate was arrived at by the working group to capture a rough order estimate for the total development effort. Actual development costs may vary widely from these gross estimates.

Development timelines were also estimated. The time to conduct the suggested R&D in a particular technical area represents the consensus view of the working group. In order to properly respect substantial development timeline uncertainties, again gross order estimates are made. The three-year lifecycle plan time scale typical of current NA-22 projects is used here as the standard unit of time, so that all projected development times to complete R&D tasks appear as multiples of three-year cycles.

Technical maturity has also been assessed for each of the technology areas by mission requirement and ConOp and is defined in accordance with the current state of technical readiness for a given approach. The assignment of low, medium, and high maturity is in general correspondence with the DoD Research, Development, Test, and Evaluation (RDT&E) Levels 6.1, 6.2, and 6.3.

For the purposes of this document, maturity levels have the following definitions:

- **High maturity [application challenge]:** The given technology is well understood and improving it requires straightforward engineering application of well-understood design principles and engineering guidelines. The process to design an application-specific integrated circuit (ASIC), for example, is highly mature; there are well-known design rules, design packages, and fabrication processes. In general, if an area is highly mature, there is little research content and commercial expertise is widely available and high quality. In general, high maturity is identified as having a path to technology application within three years, the typical length of a single NA-22 project lifecycle.
- **Medium maturity [engineering challenge]:** The given technology is understood on general principles but there may be poorly understood details and there are gaps in the engineering application. Some of the current active interrogation work can be classified as medium maturity; while the underlying scientific principles are well known and can be accurately modeled, there are significant design and engineering difficulties in applying these technologies. In general, medium maturity is identified as technology development within three to six years, and the technology development is expected to require one lifecycle to address the underlying technology development and an additional lifecycle to apply the technology.
- **Low maturity [science challenge]:** The given technology is not well understood and there are underlying research questions that must be answered before an engineering effort can begin. There may not be a clear technical path to implementation. Materials research is generally low maturity, for example. There may be significant scientific questions to answer regarding materials properties and radiation performance.

> The roles of deep traps, inclusions, or other defects, for example, are more fundamental questions relevant to the ultimate implementation an emerging material in radiation detection systems. In general, low maturity implies technology development paths requiring six to twelve years, with one or two lifecycles required to answer the fundamental research questions, one lifecycle to address the underlying technology development, and one final lifecycle to apply the technology.

The degree of risk assigned to each technology area (high, medium, low) reflects the likelihood that a given technology development effort will successfully demonstrate the projected new technical solution. In many cases there is high degree of an anti-correlation between risk and maturity. As one might expect, a more mature technology engenders substantially less risk in further development toward a solution. There are important counter examples, however, necessitating the description of development risk independent of maturity. As an example, the development of specialized electron accelerators for active interrogation might be considered low risk due to the overall level of technical understanding of such sources accumulated over decades of R&D in this area. The overall maturity level may be assigned as medium and not high, however, as a reflection of the substantial engineering issues to be faced in further developing this technology, especially for field use (e.g., compactness, portability, power requirements, cooling).

The individual sources of risk within a development effort may take on many forms. There is management risk, e.g., the risk that for a given project there is inadequate financing, a mismanaged work plan, or poor programmatic direction. For the purposes of this technical roadmap, these risks are not considered because they can all be mitigated by proper project planning and managerial oversight. Proper professional management and execution of a sound, adequately supported work plan is assumed.

Instead the focus is placed on the element of technical risk that cannot be easily mitigated: the risk that a sound, well-executed, and adequately funded project may not succeed within the lifespan of that effort. Representative examples of technical risk may include:

- Procurement of new detector materials or detectors in a given purity or performance (an overestimation of component performance).
- Unconsidered backgrounds or interferences (an overestimation of signal-to-noise ratio) in detector development.
- Underestimated system integration difficulties, requiring either more financial or personnel resources, or additional time (an overestimation of capability to meet an engineering challenge or the underestimation of the complexity).
- Unexpected technical challenges or barriers (an insufficient maturity or understanding of the fundamental physics to anticipate difficulties in development paths).

Technology Assessments by Requirement

The following are the working definitions of risk adopted by the working group along with a few representative examples:

- **Low risk:** R&D activity in which the technology reach beyond current capabilities is low. The technology may be available from another application or is a straightforward extension. For example, the application of pixilated scintillator detectors for detecting correlated photons from fission is a somewhat low-risk development effort because pixilated detectors have been widely used in high-energy physics experiments and medical applications.
- **Medium risk:** R&D activity in which there is a significant technological expansion, in either using established technologies in significantly new ways or developing a new technology with a well-grounded physical foundation. For example, developing large inorganic scintillator crystals might be viewed as medium risk, since the basic properties of crystal growth are known, the expansion coefficients can be easily measured, and there is a significant technology base upon which to draw. Active interrogation techniques using neutron beams would be medium risk; although similar techniques have been used for assay of waste drums, applying these techniques to unconstrained, unknown items could be medium risk since experience to date has been within a well-controlled and well-characterized environment.
- **High risk:** R&D activity in which there is a major technological leap required in which either a broad range of technologies must be integrated in new ways (system expansion risk) or an individual technology must be developed without the benefit of risk mitigation from other areas. In addition, there is risk that the technology may not be suited for widespread deployment due to cost, high maintenance, or inherent inability to be ruggedized. For example, the past development of large germanium diode detectors could have been viewed as high risk. Although large, high-quality germanium ingots were available and the material properties of germanium were well known, germanium detectors required significant development of contacts and material compensation before germanium gamma-ray spectrometers became widely available. Developing forward-focused beams for neutron interrogation could be considered high risk; while the underlying nuclear physics and accelerator technology are known, producing an accelerator with the dose-mitigating properties to be attractive to a wide class of users or at a price point for widespread deployment could be extremely challenging.

A measure of impact is also captured in **Tables 3**, **4**, and **5**. Impact is commonly meant to reflect the degree to which a process or technology solution improves normal operations or enables new ConOps. In the case of research, however, impact is more properly defined as the potential influence on an operation or ultimate capability, since implementation depends upon other factors, including cost, complexity, and an end user's acceptance of a given technical solution.

For the purposes of the roadmap, the low, medium, and high impact categories are defined:

- **Low impact:** Successful accomplishment of the R&D activity leads to demonstrable positive change in capabilities. Evolutionary research in general is low impact. While a decade of evolutionary research can lead to significant improvements, any given improvement is incremental only and not by itself capable of leading to major change in operations or capabilities. A reasonable conceptual analog is the automotive industry. Continuous development in areas such as weight reduction and fuel economy tends to be largely incremental. The individual application of incremental improvement is then low impact, while the cumulative improvement over many years may become medium to high impact.
- **Medium impact:** Successful accomplishment in the R&D activity leads to significant positive change in capabilities but would not by itself lead to radically new ConOps or methods of use. Much of the best long-term industrial research is medium impact; it is highly focused, rigorous, and tied to explicit improvements in specific systems. While the basic research component of Bell Laboratories is most famous, most of the research at Bell Labs was focused on applying new technology in a spiral development process to improve telephone networks. In the radiation detection field, the ^{3}He proportional counter has been a medium-impact technology. While it has been a great advance over the BF_3 tube, the BF_3 tube had many of the same features including high efficiency and insensitivity to gamma rays. The major impact of the ^{3}He tube has been to make portable field instruments much safer and more readily accepted.
- **High impact:** Successful accomplishment of the R&D activity leads to new capabilities or enables new operational concepts. Notable examples of high-impact research include the invention of the transistor, development of the first radar system, and the discovery of the first nuclear chain reaction. In the commercial sector, high-impact research examples should include leaps in computer performance and medical technology breakthroughs, such as gene therapy and stem cell research. In the radiation detection field, the development of germanium diode detectors has been high impact since it enabled the entire discipline of high-resolution gamma-ray spectroscopy. Nuclear analysis as we now know it would be completely impossible without HPGe detectors.

The technology development data generated in the roadmap process is presented in Appendices B, C, and D; an analysis of the highest-impact R&D directions is found in the sections below. We complete the discussion by presenting the underlying assumptions that influenced the rankings and decisions. Each mission requirement is considered independently and each technical area is addressed separately.

When assigning impact to individual technology development areas, a systems-level viewpoint was adopted. Though systems-level development is usually considered somewhat beyond the development scope of activities for this program, it was recognized that no single technology, even if fully developed, will in itself solve the very difficult detection challenges envisioned for scenarios of interest to the nonproliferation community. This system view approach attempts to link R&D technical areas that, when mature and combined, will yield a demonstrable capability enhancement applicable to a wide array of users. This approach places more emphasis on the expected outcome of all research related to a complete solutions rather than an individual component.

Requirement 1: Detect Shielded HEU

Table B1 in Appendix B lists all of the technology development topics considered responsive to mission area Requirement 1, detect shielded HEU. For this requirement, actively induced signatures are anticipated to be one of the few truly high impact avenues available to detect HEU in most situations of interest, given the current understanding of the problem. The archetypal system envisioned for shielded HEU detection is one that exploits the high-multiplicity, time-correlated signatures of fission induced by an external source of either gamma or neutron radiation of sufficient energy and intensity to allow a favorable signal-to-noise ratio and, thereby, high-confidence detection. This envisioned system requires new detectors that can exploit the time-correlated fission signatures and tolerate the potentially harsh radiation environment in close proximity to the source of interrogation radiation. A radiation source will be required that can produce the necessary radiation with sufficient intensity and timing to induce the required signature profile. Given this vision of the capability necessary to address the requirement, we developed the following assessment of the various R&D avenues introduced in Table B1.

The impact of R&D by technology across the three generalized ConOps for Requirement 1 provides a requirement-level view of all the R&D needs to provide demonstrable capability enhancement (**Table 3**), and provides a means for prioritizing R&D investments. The overall investment prioritization will be discussed in the Comprehensive Technology Development Roadmap section (page 53), where priorities across requirements are introduced. It is clear that this impact-level view is heavily influenced by the assumptions of system-level needs to achieve this requirement. For this reason, regularly reassessing the validity of the underlying system assumptions is necessary as new science and enabling technology becomes available. The highest-impact R&D needs by technology for Requirement 1 are discussed after Table 3.

Gamma and neutron detection—timing, multiplicity, and signatures. Investigate time-correlated, high-multiplicity, gamma-ray and neutron signatures of SNM. R&D for gamma-ray detectors with ability to exploit the time-correlated signatures and operate in high-radiation environments typical of active interrogation.

High-resolution gamma detectors. R&D for new detectors capable of resolving important gamma and x-ray lines for analysis of actively induced signatures. Important characteristics include low weight and power, room-temperature operation, and ability to function in high-radiation environments typical of active interrogation.

Large-area detectors for high-energy neutrons. Large-area detectors necessary to exploit induced time-correlated signatures. Detector must function in high-radiation environment typical of active interrogation.

Solid-state neutron detectors. Solid-state detectors for neutron detection are desired to replace current gas-filled detectors in field systems. The preference is in developing detectors exhibiting higher efficiency and lower power consumption.

Photon sources—broad energy spectrum. Broad energy spectrum photon sources are envisioned as a component of active interrogation systems for inducing fission (time-correlated signatures) and potentially other nuclear signatures.

Photon sources—monoenergetic. Monoenergetic photon sources are of particular interest because of the potential to increase sensitivity of a detection system while lowering the radiation dose to the object and personnel. Wide energy-range tuning is ultimately desirable, though narrow energy-range tuning or selectability is more practical nearer-term goal. Such a source could be vital for exploitation of NRF signatures.

Table 3. Requirement 1—Impact of R&D on shielded HEU detection by technology area.

R&D Technical Area	R&D Technology Class	Characterize	Contain/Screen	Search
Gamma correlation	Gamma detection—timing, multiplicity, signatures	1	1	1
Gamma imaging	Electronically collimated system	2	3	3
	Mechanically collimated systems	2	3	3
Gamma spectroscopy	Algorithms for ID in active systems	2	3	3
	High-resolution gamma-ray detectors	1	3	2
Neutron correlation	Large-area detectors—high energy	2	1	1
	Large-area detectors—thermal	3	2	3
	Solid-state neutron detectors	3	1	1
	Alternate neutron detectors	3	3	2
	Neutron detection—timing, multiplicity, signatures	1	1	1
Neutron imaging	3D neutron tracking detector	2	3	3
	Neutron imaging detectors	2	3	3
Neutron spectroscopy	Ultra high-resolution neutron spectrometry	3		
	Neutron spectroscopy systems	2	3	3
Photon source	Broad spectrum	1	1	1
	Monoenergetic	1	1	1
Neutron Source	Accelerator based	1	1	1
	Radioactive source based	1	1	1
Other Source	Muon sources, proton sources, ...			

Green cells indicate high-impact technologies.

Yellow cells indicate medium-impact technologies.

Red cells indicate low-impact technologies.

Neutron sources—accelerator based. Accelerator-based neutron sources are anticipated to be useful in exploiting fission and other nuclear signatures in HEU. Accelerator-based systems are desirable over radioactive sources because of their potential to reduce dose, on/off ability, potential for selectable energy, and higher intensity.

Neutron sources—radioactive sources. Radioactive-based neutron sources may have limited applicability to shielded SNM detection. Sources could include Cf or Pu-Be or Am-Be neutron sources. Difficulties include shielding requirements and other fieldability issues.

Requirement 2: Detect SNM at a Standoff Distance

The requirement to detect SNM at standoff distances represents a significant technical challenge, particularly when considering cases where the SNM target is moderately to significantly shielded. As discussed in detail in the Requirement 2: Detect SNM at Standoff Distances section (page 29), the standoff detection of SNM is increasingly difficult when distances of tens to hundreds of meters and beyond are considered. As separation between source and observer increases, a limit is eventually approached beyond which it is impossible to determine with certainty the presence of an SNM source by observation of its passive radiation signature. Active interrogation may somewhat extend the range of detectability, though this has its limits as well. Two archetypal systems are envisioned to frame the discussion of technical solutions to this requirement and help in the R&D assessment. First, radiation imaging techniques relying solely on the passive radiation signatures intrinsic to SNM is widely recognized as a methodology to reduce background contribution and, thereby, increase detection range. The usefulness of such systems is largely dependent on the assumption that the SNM target is either unshielded or lightly shielded as defined earlier in this document. There are user-defined scenarios in which this assumption is consistent with current ConOps. As the second exemplar to guide the evaluation process, an active interrogation system is considered in which a source of radiation is used to stimulate observable signatures in the SNM coupled with appropriate detectors to detect the return signature. This methodology has the potential of increasing detection range by virtue of the strength, control, and time-tagging of the induced radiation vice that of passive emission, or by the application of bistatic detection modalities.

Not included are non-radiometric methods or alternate methods for SNM detection. While modest work has been done in this area, it has not yet yielded a technique that is both applicable to the scenarios considered here and offers significantly more sensitivity at a given distance. It is the recommendation here that an effort to identify new alternate methods for detection continues as signatures and observables efforts until such time that performance advantage for a scenario of interest is identified. The data is found in **Appendix C, Table C1**.

Just as with Requirement 1, the impact of R&D by technology across the three generalized ConOps for Requirement 2 provides a requirement-level view of all the R&D needs to provide demonstrable capability enhancement (see **Table 4**),

Technology Assessments by Requirement

and provides a means for prioritizing R&D investments. The overall investment prioritization will be discussed in the Comprehensive Technology Development Roadmap section (page 53) where priorities across requirements are introduced. Regular reassessment of the validity of the underlying system assumptions is necessary as new science and enabling technology becomes available. The highest-impact R&D needs by technology for Requirement 2 are discussed after Table 4.

Gamma imaging—mechanically collimated systems. Imaging systems that utilize a mechanical or physical method to image a radiation source. Examples include coded-aperture detector techniques. These techniques are in general mature for passive detection scenarios and ready for adoption by a particular user. R&D is required for the integrating these techniques into active interrogation modalities.

Gamma imaging—electronically collimated systems. Electronically collimated radiation imaging systems reconstruct the trajectory of each radiation event by electronic means. This research area includes Compton scatter cameras. This area is of growing maturity, but research issues continue to focus on better reconstruction algorithms, multi-pixel detectorization and readout, and full particle tracking. Significant issues may arise when integrated as a component of an active interrogation system.

Table 4. Requirement 2—Impact of R&D on standoff SNM detection by technology area.

R&D Technical Area	R&D Technology Class	Characterize	Contain/Screen	Search
Gamma correlation	Gamma detection—timing, multiplicity, signatures	2	2	2
Gamma imaging	Electronically collimated system	1	1	1
	Mechanically collimated systems	1	1	1
Gamma spectroscopy	Algorithms for ID in active systems	1	1	1
	High-resolution gamma-ray detectors	1	1	1
Neutron correlation	Large-area detectors—high energy	2	1	1
	Large-area detectors—thermal	3	1	1
	Solid-state neutron detectors	3	3	3
	Alternate neutron detectors	3	3	3
	Neutron detection—timing, multiplicity, signatures	1	1	1
Neutron imaging	3D neutron tracking detector	1	1	1
	Neutron imaging detectors	1	1	1
Neutron spectroscopy	Ultra high-resolution neutron spectrometry	3		
	Neutron spectroscopy systems	3	3	3
Photon source	Broad spectrum	1	1	1
	Monoenergetic	1	1	1
Neutron Source	Accelerator based	1	1	1
	Radioactive source based	3	3	3
Other Source	Muon sources, proton sources, ...	1		

Green cells indicate high-impact technologies.
Yellow cells indicate medium-impact technologies.
Red cells indicate low-impact technologies.

Neutron imaging—3D tracking detectors. Neutron tracking detectors are analogous to Compton Scattering gamma-ray imaging techniques in that they use kinematic relationships to reconstruct the trajectory of a detected neutron. These techniques are applicable to standoff detection in both the passive and active modalities and significant R&D efforts remain particularly for the direct detection of energetic (fast) neutrons.

Neutron imaging detectors. The neutron imaging detectors category includes techniques for imaging thermal neutrons and includes many conventional systems. These systems are by and large ready for user adoption in appropriate ConOps. Integration into active interrogation systems will present new R&D challenges.

Gamma and neutron detection—timing, multiplicity, and signatures. Investigate time-correlated, high-multiplicity, gamma-ray and neutron signatures of SNM. R&D is required for gamma-ray detectors with the ability to exploit the time-correlated signatures and operate in high-radiation environments typical of active interrogation.

High-resolution gamma detectors. R&D for new detectors capable of resolving important gamma-ray lines for analysis of actively induced signatures. Important characteristics include low-power, room-temperature operation, and ability to function in high-radiation environments typical of active interrogation.

Algorithms for active systems. Develop algorithms that yield the highest possible system sensitivity and specificity from active interrogation systems. This topic will include the treatment of background, timing information, evaluation of correlated and coincident signatures, and data fusion across multiple detector types.

Large-area detectors for high-energy neutrons. Large-area detectors necessary to exploit induced time-correlated signatures optimized for energetic (fast) neutrons. Detector must function in high-radiation environment typical of active interrogation.

Large-area detectors for low-energy neutrons. Large-area detectors necessary to exploit induced time-correlated signatures optimized for low-energy (thermal) neutrons. Detector must function in high-radiation environment typical of active interrogation.

Photon sources—broad energy spectrum. Broad energy spectrum photon sources are envisioned as a component of active interrogation systems for inducing fission (time-correlated signatures), and potentially other nuclear signatures. Of particular interest are focused, high-energy beams with the ability to penetrate hundreds of meters of air and significantly shielded threats.

Photon sources—monoenergetic. Monoenergetic photon sources are of particular interest because of the potential to increase sensitivity of a detection system while reducing the radiation dose to the object. Narrow energy-range tuning ability may be advantageous for particular ConOps. Such a source could be vital for exploiting NRF signatures. Of particular interest are focused high-energy beams with the ability to penetrate hundreds of meters of air and significantly shielded threats.

Neutron sources—accelerator based. Acceleration-based neutron sources are anticipated to be useful in exploiting fission and other nuclear signatures in HEU. Accelerator-based systems are desirable over radioactive sources because of their potential to reduce dose, on/off ability, potential for selectable energy, and high intensity. Focused beams for interrogation at tens of meters and beyond are desired.

Other sources. System studies of the applicability of other stimulating radiation in the generation and exploitation of induced signatures. Exotic beams of charged particles, particularly muons and protons, may be of interest. The goal is highly focused kilometer-range beams that induce unique observable signatures in SNM.

Requirement 3: Detect Shielded Plutonium

The R&D needs discussion for detecting shielded plutonium is influenced by the assumption that systems for the detection of plutonium would continue to exploit the passive radiation signatures of plutonium. While the potential of active techniques in detecting plutonium is appreciated, advances made in active interrogation R&D for shielded HEU detection are expected to be applicable to shielded plutonium discovery with little additional work. Therefore, the archetype system concept considered for this requirement is based on the passive detection of gamma and neutron radiation characteristic of plutonium isotopes. With a few important exceptions, the fundamental physics of emission of gamma and neutron radiation from plutonium are well understood. See data in **Appendix D, Table D1.**

Just as with the first two requirements, the impact of R&D by technology across the three generalized ConOps for Requirement 3 provides a requirement-level view of all the R&D needs to provide demonstrable capability enhancement (**Table 5**), and provides a means for prioritizing R&D investments. The overall investment prioritization will be discussed in the Comprehensive Technology Development Roadmap section (page 53) where priorities across requirements are introduced. It is clear that this impact-level view is heavily influenced by the assumptions of system-level needs to achieve this requirement. As for the other requirements, the regularly reassessing the validity of the underlying system assumptions is necessary as new science and enabling technology becomes available. The highest-impact R&D needs by technology for Requirement 3 are discussed after Table 5.

Gamma and neutron detection—timing, multiplicity, and signatures. Investigate time-correlated, high-multiplicity, gamma-ray and neutron signatures of SNM. R&D for gamma-ray and neutron detectors with the ability to exploit the time-correlated signatures from spontaneous fission.

Technology Assessments by Requirement

Gamma imaging—mechanically collimated systems. Imaging systems that utilize a mechanical or physical method to image a radiation source. Examples include coded-aperture detector techniques. These techniques are in general mature for passive detection scenarios and ready for adoption by a particular user. While important, these techniques were not viewed as high impact to all generalized ConOps for shielded plutonium detection. This is mostly due to the lower total sensitivity of this technique when compared to time-correlated signatures or other detection modalities.

Gamma imaging—electronically collimated systems. Electronically collimated radiation imaging systems reconstruct the trajectory of each radiation event by electronic means. This research area includes Compton scatter cameras. This area is maturing, but research issues continue to focus on better reconstruction algorithms, multi-pixel detectorization and readout, and full particle tracking. While important, these techniques were not viewed as high impact to all generalized ConOps for shielded plutonium detection. In general, this is because of the penalty in overall sensitivity when imaging a source.

Table 5. Requirement 3—Impact of R&D on shielded plutonium detection by technology area.

R&D Technical Area	R&D Technology Class	Characterize	Contain/Screen	Search
Gamma correlation	Gamma detection—timing, multiplicity, signatures	1	1	1
Gamma imaging	Distributed sensor systems	3	2	3
	Electronically collimated system	1	2	2
	Mechanically collimated systems	1	2	2
Gamma spectroscopy	Algorithms for ID in active systems	3	3	3
	High-resolution gamma-ray detectors	1	1	1
Neutron correlation	Large-area detectors—high energy	1	1	1
	Large-area detectors—thermal	1	1	1
	Solid-state neutron detectors	2	1	1
	Alternate neutron detectors	3	3	2
	Neutron detection—timing, multiplicity, signatures	1	1	1
Neutron imaging	3D neutron tracking detector	1	2	2
	Neutron imaging detectors	1	2	2
Neutron spectroscopy	Ultra high-resolution neutron spectrometry	3		
	Neutron spectroscopy systems	2	3	3
Photon source	Broad spectrum	2	2	2
	Monoenergetic	2	2	2
Neutron Source	Accelerator based	2	2	2
	Radioactive source based	2	2	2
Other Source	Muon sources, proton sources, ...			

Green cells indicate high-impact technologies.
Yellow cells indicate medium-impact technologies.
Red cells indicate low-impact technologies.

High-resolution gamma detectors. R&D for new detectors capable of resolving important gamma-ray lines for analysis of actively induced signatures. Among the important characteristics are low power consumption and room-temperature operation. High-resolution gamma-ray detectors are considered critical to enhanced capability in shielded plutonium detection.

Large-area detectors for high-energy neutrons. Large-area detectors necessary to exploit time-correlated signatures optimized for energetic (fast) neutrons. Detectors must be capable of resolving important time structure of correlated signatures.

Large-area detectors for low-energy neutrons. Large-area detectors necessary to exploit time-correlated signatures optimized for low-energy (thermal) neutrons. Detectors must be capable of resolving important time structure of correlated signatures.

Solid-state neutron detectors. Solid-state detectors for neutron detection are desired to replace current gas-filled detectors in field systems. The preference is for detectors with better efficiency and lower power consumption.

Fast neutron imaging—3D tracking detectors. Neutron tracking detectors are analogous to Compton scattering gamma-ray imaging techniques in that they use kinematic relationships to reconstruct the trajectory of a detected neutron. While important, these techniques were not viewed as high impact to all generalized ConOps for shielded plutonium detection. In general, this is because of the penalty in overall sensitivity when imaging a source.

Thermal neutron imaging detectors. The neutron imaging detectors category includes techniques for imaging thermal neutrons and includes many conventional systems. These systems are by and large ready for user adoption in appropriate ConOps. While important, these techniques were not viewed as high impact to all generalized ConOps for shielded plutonium detection. In general, this is because of the penalty in overall sensitivity when imaging a source.

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Comprehensive Technology Development Roadmap

This section integrates the individual technology rankings and data presented for the three portfolio-level requirements to create a comprehensive technical roadmap across the portfolio. Following integration, we developed a prioritized list of R&D technical areas to provide a guide for soliciting new projects and facilitate prioritizing highly ranked proposals in the selection and funding process. To determine direction for the program, it was deemed appropriate to evaluate the current portfolio and determine where additional funds are required in light of the established set of priorities.

Prioritization Across Portfolio Requirements

The prioritization parameters of maturity, risk, and impact are integrated across the three portfolio requirements for evaluation and ultimate prioritization. As discussed in the Technology Assessment by Requirement section, these parameters each play a role in the developing new R&D priorities. In this section, we combine and compare them across generalized ConOps and requirements to arrive at a prioritized investment strategy.

Maturity: As a first step, it is necessary to evaluate the current maturity level across the R&D landscape. As seen in **Table 6**, technical maturity of the R&D areas considered in this portfolio roadmap are mostly in the DoD RDT&E Level 6.1 (i.e., early applied science and engineering stage). This maturity level is consistent with the overall NA-22 goal of demonstrating enhanced detection capabilities by beginning Level 6.1 R&D at the proof-of-concept level and maturing it to a point where it can be demonstrated to potential end users at Level 6.3a. Maturity plays an important role in portfolio-wide prioritization in that technical areas that are less mature often have the greatest potential to yield substantially new detection capabilities that may enable new ConOps. This philosophy is at the core of the NA-22 office approach to capability enhancement and long-term R&D support, and is exemplified in this portfolio. It is, however, recognized that the more mature state of some R&D areas may lead to a more near-term and incremental capability improvement. Technical areas currently exhibiting medium to high levels of maturity are, by and large, areas where recent substantial investments by NA-22, other DOE offices, and some interagency R&D offices have enabled this state of maturity. It is this long-term investment that has matured these technologies to their current state.

There are several notable exceptions in this table to the general trend of considering capability improving technologies for SNM detection that are currently only at the 6.1 maturity level (i.e., mechanically collimated gamma-ray imaging system, large-area thermal neutron detectors, thermal neutron imaging detectors, broad spectrum photon sources, and radioisotope-based sources for active interrogation). While these individual components are somewhat more developmentally mature, they may be considered important contributors to new overall detection capability, perhaps exploiting a novel detection modality, such as time-correlated signature detection, for example.

Mechanically collimated gamma-ray imaging systems were considered to have a maturity level of 6.2 for all requirements and ConOps since there exists a wealth of knowledge and expertise in the R&D community and the commercial sector for developing these systems. In the area of neutron detection, both large-area thermal neutron detectors and thermal neutron imaging were considered to be greatly mature. Many of the remaining development issues for these systems are likely to focus on technology integration and engineering rather than basic or applied science. In the case of thermal neutron imaging, NA-22 has a long history of supporting the development of these systems, and they are currently at a state where they could be readily demonstrated. In the area of sources of radiation, both broad spectrum bremsstrahlung gamma-ray sources and radioisotope-based sources are considered mature in the context of the portfolio requirements. System integration and fieldability issues are the major considerations for all of the R&D technical areas currently at the 6.2 maturity level or above.

Table 6. Current maturity of R&D technology class by generalized ConOps and portfolio requirements.

		Shielded HEU Detection			Standoff Detection of SNM			Shielded Pu Detection		
R&D Technical Area	R&D Technology Class	Characterize	Contain/Screen	Search	Characterize	Contain/Screen	Search	Characterize	Contain/Screen	Search
Gamma correlation	High-rate, high-multiplicity gamma detector	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Gamma imaging	Distributed sensor systems							6.1	6.1	6.1
	Electronically collimated system	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
	Mechanically collimated systems	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Gamma spectroscopy	Algorithms for ID in active systems	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
	High-resolution gamma-ray detectors	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Neutron correlation	Alternate neutron detector	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
	Large-area detectors—high energy	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
	Large-area detectors—thermal	6.2	6.2	6.2	6.2	6.2	6.1	6.2	6.2	6.2
	Solid-state neutron detectors	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
	Timing and multiplicity	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Neutron imaging	3D neutron tracking detector	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
	Neutron imaging detectors	6.2	6.2	6.2	6.2	6.2	6.2	6.3	6.3	6.3
Neutron spectroscopy	Ultra high-resolution neutron spectrometry	6.2			6.2			6.1		
	Neutron spectroscopy systems	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Photon source	Broad spectrum	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
	Monoenergetic	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Neutron source	Accelerator based	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
	Radioactive source based	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Other source	Muon sources, proton sources, ...	6.0			6.0			6.0		

Green cells indicate high-impact technologies.

Yellow cells indicate medium-impact technologies.

Red cells indicate low-impact technologies.

Risk: The technical risk associated with an R&D effort is also evaluated in this roadmap (**Table 7**) as it may play an important role in the shaping of a comprehensive R&D program. In order to ensure that non-trivial leaps in detection capability are valued and sought out in this program, significant technical risk must often be accepted as a cost of conducting business. Incremental capability improvements and near-term solutions to pressing end-user problems often necessitate less-risky approaches. A well-managed program balances technical risk to achieve the appropriate mix of long-term, far-reaching developments with nearer-term, ready solutions. While this program leans in favor of the former, there is a constant struggle to obtain the appropriate balance.

There are additional risk-related considerations. First, it is often difficult if not impossible to assess R&D risk across the breadth of a system solution approach to detection and attribute individual component contributions to risk. Since this R&D

Table 7. Technical risk of R&D technology class by generalized ConOps across all portfolio requirements.

		Shielded HEU Detection			Standoff Detection of SNM			Shielded Pu Detection		
R&D Technical Area	**R&D Technology Class**	**Characterize**	**Contain/Screen**	**Search**	**Characterize**	**Contain/Screen**	**Search**	**Characterize**	**Contain/Screen**	**Search**
Gamma correlation	High-rate, high-multiplicity gamma detector	2	2	2	2	2	2	2	2	2
Gamma imaging	Distributed sensor systems							1	1	1
	Electronically collimated system	1	1	1	1	1	1	1	1	1
	Mechanically collimated systems	2	2	2	2	2	2	2	2	2
Gamma spectroscopy	Algorithms for ID in active systems	1	1	1	1	1	1	1	1	1
	High-resolution gamma-ray detectors	1	1	1	1	1	1	1	1	1
Neutron correlation	Alternate neutron detectors	2	2	2	2	2	2	2	2	2
	Large-area detectors—high energy	1	1	1	1	1	1	2	2	2
	Large-area detectors—thermal	2	2	2	2	2	1	3	3	3
	Solid-state neutron detectors	1	1	1	1	1	1	1	1	1
	Timing and multiplicity	2	2	2	2	2	2	2	2	2
Neutron imaging	3D neutron tracking detector	2	2	2	1	1	1	2	2	2
	Neutron imaging detectors	2	2	2	2	2	2	2	2	2
Neutron spectroscopy	Ultra high-resolution neutron spectrometry	3			3			2		
	Neutron spectroscopy systems	2	2	2	2	2	2	2	2	2
Photon source	Broad spectrum	3	3	3	3	3	3	3	3	3
	Monoenergetic	1	1	1	1	1	1	1	1	1
Neutron source	Accelerator based	2	2	2	1	2	1	2	2	2
	Radioactive source based	3	3	2	2	2	2	3	3	2
Other Source	Muon sources, proton sources, ...				1					

Green cells indicate high-impact technologies.
Yellow cells indicate medium-impact technologies.
Red cells indicate low-impact technologies.

program tends to concentrate on component solutions, yet must place component development in the context of a detection system, this level of risk evaluation is extremely difficult. Second, it is the exception rather than the rule that multiple like technical approaches in our program are available for a given technical approach. It is then difficult to assess comparative risk and select on this basis. Finally, in a practical sense, and somewhat contrary to other approaches of risk mitigation, the indication of a particular R&D technical area as technically risky suggests that more resources should be committed to perhaps fund multiple parallel approaches. In this roadmapping effort, mitigating risk was an implicit influence on the derived budget figures attributed to each technical area development effort. If a technical area is deemed high impact and, therefore, critical to the development of new capability, and is ranked as a high technical risk, then a prudent approach suggests starting multiple parallel R&D projects in that area, and establishing clear objectives along with a schedule for down-selection.

The risk associated with the technical R&D classes discussed in this roadmap can be found in Table 7. It should be noted that many of the most critical or high-impact R&D technical areas, found in **Table 8**, are also ranked high risk. The risk parameter is also highly anti-correlated with the maturity rankings, as one would expect. Lower-maturity R&D technical areas are also expected to have high technical risk. There are, however, interesting exceptions where technology classes exhibit low maturity and moderate risk, notably in correlated signatures, neutron imagers that perform full kinematic reconstruction of events, and accelerator-based neutron sources.* Significant prior work has already demonstrated the applicability of these concepts to the portfolio requirements, thereby reducing the overall risk. For these reasons, investments in these areas may be particularly advantageous, especially when also correlated with high portfolio-level impact.

Impact: The single most important factor by far in prioritization across and within portfolio requirements is the potential impact derived from developing an R&D technology class. As discussed in the Technology Assessment by Requirement section (page 39), the assignment of an impact rating for an R&D technology class is determined by considering an idealized detection system that addresses the portfolio requirements. In this way, R&D technology classes that are an integral component of a requirement-level archetypal detection system are assigned a higher impact rating. An important implication of this approach is that care must be taken when conducting program builds not to orphan individual R&D efforts that appear in a critical, high-impact pathway to a new detection capability demonstration because they might in isolation have a lower individual expected impact.

The impact of R&D technology classes across all generalized ConOps and portfolio requirements is provided in **Table 8**. The utility of these data are twofold. First, it is possible to interpret the system-level R&D requirements by observing the relationship between high- and medium-impact R&D technology classes per ConOp

* While commercially available accelerator-based neutron generators exist, further development is required to address the need for directionality, lower dose, high intensity, and durability/lifetime (i.e., maturity) issues.

Table 8. Impact of technology class by generalized ConOps across all portfolio requirements.

R&D Technical Area	R&D Technology Class	Shielded HEU Detection			Standoff Detection of SNM			Shielded Pu Detection		
		Characterize	Contain/Screen	Search	Characterize	Contain/Screen	Search	Characterize	Contain/Screen	Search
Gamma correlation	Gamma detection—timing, multiplicity, signatures	1	1	1	2	2	2	1	1	1
Gamma imaging	Distributed sensor systems							3	2	3
	Electronically collimated system	2	3	3	1	1	1	1	2	2
	Mechanically collimated systems	2	3	3	1	1	1	1	2	2
Gamma spectroscopy	Algorithms for ID in active systems	2	3	3	1	1	1	3	3	3
	High-resolution gamma-ray detectors	1	3	2	1	1	1	1	1	1
Neutron correlation	Large-area detectors—high energy	2	1	1	2	1	1	1	1	1
	Large-area detectors—thermal	3	2	3	3	1	1	1	1	1
	Solid-state neutron detectors	3	1	1	3	3	3	2	1	1
	Alternate neutron detectors	3	3	2	3	3	3	3	3	2
	Neutron detection—timing, multiplicity, signatures	1	1	1	1	1	1	1	1	1
Neutron imaging	3D neutron tracking detector	2	3	3	1	1	1	1	2	2
	Neutron imaging detectors	2	3	3	1	1	1	1	2	2
Neutron spectroscopy	Ultra high-resolution neutron spectrometry	3			3			3		
	Neutron spectroscopy systems	2	3	3	3	3	3	2	3	3
Photon sources	Broad spectrum	1	1	1	1	1	1	2	2	2
	Monoenergetic	1	1	1	1	1	1	2	2	2
Neutron sources	Accelerator based	1	1	1	1	1	1	2	2	2
	Radioactive source based	1	1	1	3	3	3	2	2	2
Other sources	Muon sources, proton sources, ...				1					

Green cells indicate high-impact technologies.
Yellow cells indicate medium-impact technologies.
Red cells indicate low-impact technologies.

(as seen by viewing down each table column). This system-level view is illustrated in **Figures 3**, **4**, and **5** for each of the three portfolio requirements for one example ConOp. These figures show the relationship and between the high- and medium-impact technologies and increasing capability. As investment time increases, the capability also increases, reflecting the maturation of funded R&D. The green vertical arrows or high-impact R&D technical classes are on the critical path to new capability demonstration.

In addition, it is possible to compare respective levels of impact of individual technology classes across the entire portfolio by summing impact across table rows. A new parameter, the portfolio-wide impact or *total impact*, can then be introduced to facilitate the interpretation of the relative impact of an R&D

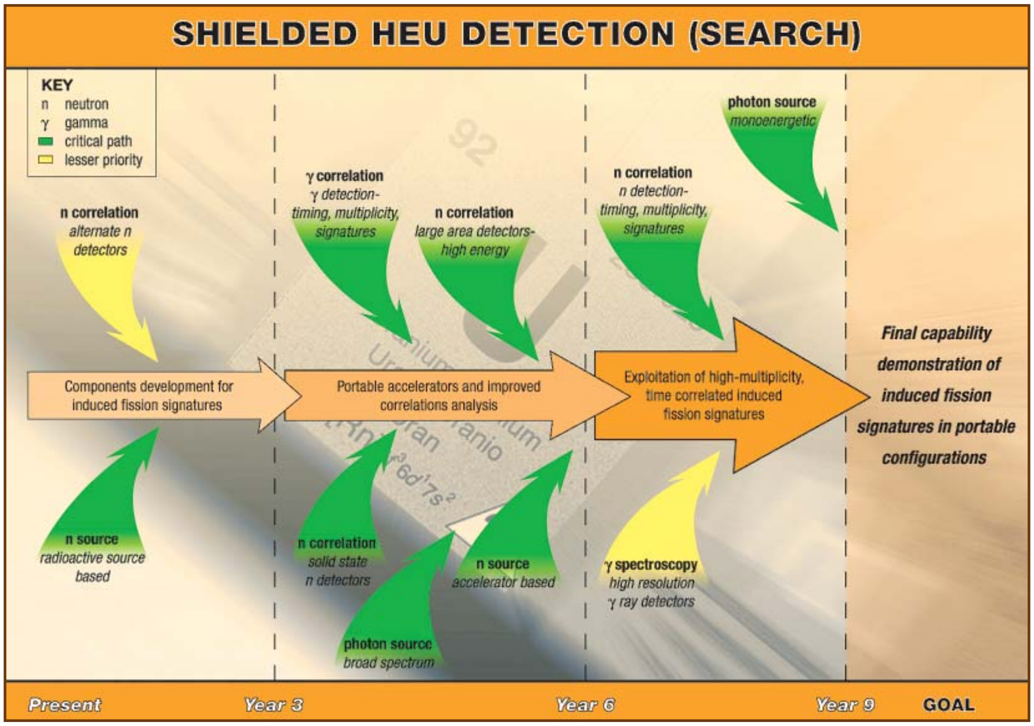

Figure 3. System-level view of the critical path technologies for the shielded HEU detection requirement in the Search ConOp.

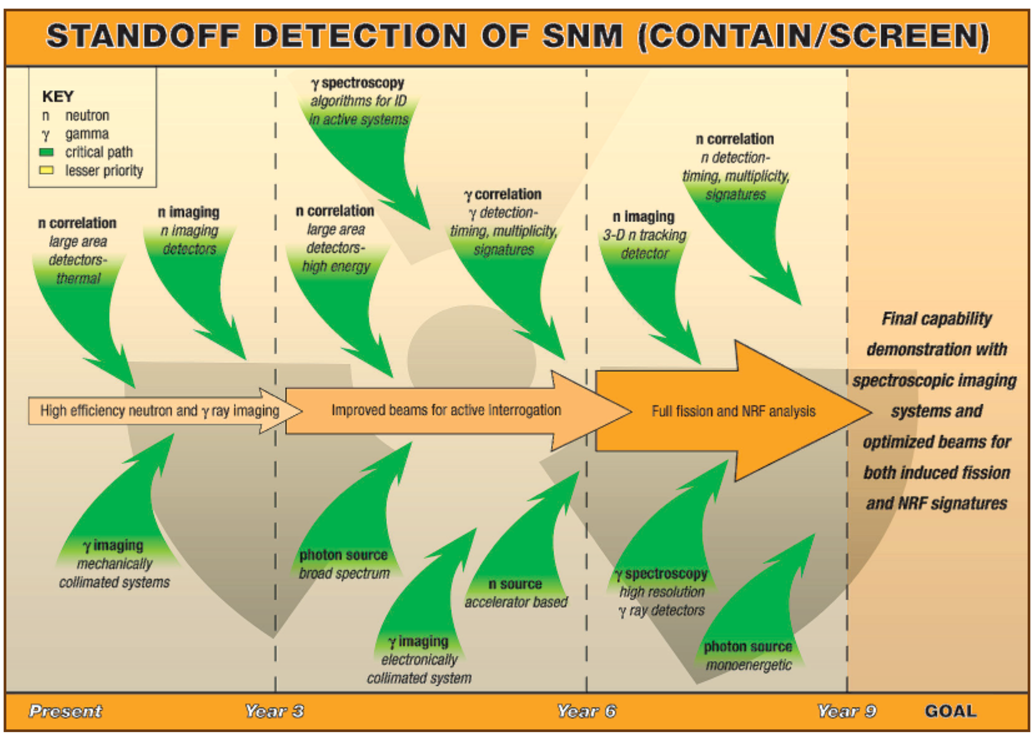

Figure 4. System-level view of the critical path technologies for the standoff detection of SNM requirement in the Contain/Screen ConOp.

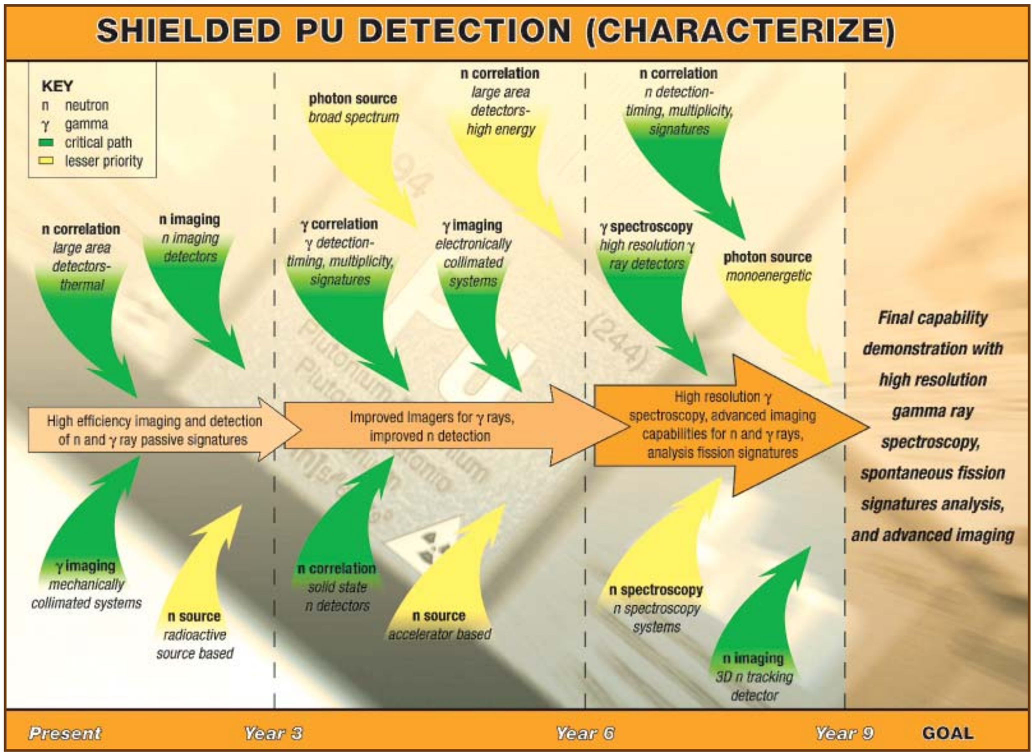

Figure 5. System-level view of the critical path technologies for the shielded plutonium detection requirement in the Characterize ConOp.

technology class across the portfolio. The total impact is calculated by applying a relative weighing for each impact score and summing across the nine generalized ConOp portfolio requirement areas. A high-impact rank is assigned a numerical score of 1, a medium-impact rank is assigned a numerical score of 0.33, and a low-impact rank is assigned a numerical score of 0. This summation across a R&D technology class, or row, yields the total impact value.

The three R&D technology classes that possess the highest total impact score are (1) high-multiplicity time-correlated signatures of SNM, (2) large-area detectors for energetic neutrons, and (3) high-resolution gamma-ray detectors for gamma spectroscopy. Each of these R&D technology classes plays a major role and has the potential to yield high-impact solutions to all three portfolio requirements. A very-high value is placed on the detection potential of high-multiplicity time-correlated events from fission, both intrinsic and induced. If successful, this R&D area will have major implications on the detection and identification of SNM in all ConOps because it is the unique signature shared by all SNM types. Large-area detectors for energetic neutron detection are a technology area that was not singled out as a major need prior to this roadmap assessment. This unexpected emphasis on large-area neutron detectors for energetic neutrons, with energies above thermal, is a result of the portfolio-wide focus on high-multiplicity, time-correlated signatures of SNM. R&D for these detectors is critical for exploiting the unique correlated signatures of SNM in both passive and active systems. The development of high-resolution gamma-ray spectrometers is also considered critical to the exploitation of correlated signatures, but is in addition widely recognized as an integral part of every ConOp and user mission as a high-performance characteristic gamma detection and identification tool. These devices are one of the few field-capable tools available to definitively identify a radioactive material as SNM. Their continued improvement will significantly enhance U.S. government capability across the widest possible user base.

Tables 6, 7, and 8 individually capture the portfolio-wide maturity, risk, and impact of the R&D technology classes. To be useful in the process of selecting new proposals to build future programs, the data in these tables is used to derive a priority ordering of the technology classes. The prioritized R&D list is generated by first ordering technology classes by ascending maturity, then by descending total impact. The reasoning for this ordering of technology classes is that R&D areas that offer greater total impact will provide capabilities to a wider array of the generalized ConOps across the three portfolio requirements. This ordering also places more importance on lower-maturity and typically higher-risk R&D, thereby providing greater opportunity for revolutionary improvement in capability. The net result of this ordering is to place higher priority on R&D that will have the greatest impact across the portfolio requirements and offer the best opportunity at demonstrating a revolutionary technical capability.

The prioritized R&D investment strategy is presented **Table 9**. The order of R&D technology classes follows from the prioritization methodology described above. The R&D technology classes are then grouped into first-, second-, and third-priority categories. These funding priority categories reflect the difference between relative rankings of technology classes. The first-priority category contains R&D areas that are low maturity, medium-to-high risk, and have a total impact score of at least seven indicating that the R&D area will provide a significant impact to all of the requirements. The R&D technology classes within a priority category are accorded roughly equal importance; however, they are listed in descending order of total impact. The second-priority category consists of R&D technology classes that are of low maturity and have a total impact ranking greater than four but less than seven. This total impact range corresponds to technologies that are of high impact to at least one portfolio requirement. The third-priority category contains R&D areas that have a high-to-medium maturity and a total impact score greater than four but less than seven. While they share the same total impact characterization with the medium-priority category, these R&D areas are much more mature and typically at a stage where capability has been demonstrated or could be within a short time. Therefore, allocations of scarce funds to these mature areas are not encouraged except in cases where specific user interest is forthcoming.

Four R&D areas are not represented in any prioritization group in Table 10; distributed sensor systems, alternate neutron detectors, ultra high-resolution neutron spectrometers, and other sources, such as non photon or neutron. These R&D technology classes are not currently considered to provide sufficient impact across the

Table 9. Prioritized R&D investment strategy. Also shown is the estimated, unconstrained R&D cost ($M/yr) and development time to demonstration required for the prioritized technology areas.

	R&D Technical Area	R&D Technology Class	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
First Priority	Neutron correlation	Neutron detection—timing, multiplicity, signatures	$3	$3	$3	$3	$3	$3	$3	$3	$3
First Priority	Neutron correlation	Large-area detectors—high energy	$2	$2	$2	$2	$2	$2			
First Priority	Gamma spectroscopy	High-resolution gamma-ray detectors	$10	$10	$10	$10	$10	$10	$10	$10	$10
First Priority	Gamma correlation	Gamma detection—timing, multiplicity, signatures	$3	$3	$3	$3	$3	$3			
First Priority	Neutron source	Accelerator based	$8	$8	$8	$8	$8	$8			
First Priority	Photon source	Broad spectrum	$8	$8	$8	$8	$8	$8			
First Priority	Photon source	Monoenergetic	$20	$20	$20	$20	$20	$20	$20	$20	$20
Second Priority	Neutron imaging	3D neutron tracking detector	$3	$3	$3	$3	$3	$3	$3	$3	$3
Second Priority	Gamma imaging	Electronically collimated system	$10	$10	$10	$10	$10	$10			
Second Priority	Gamma spectroscopy	Algorithms for ID in active systems	$2	$2	$2	$2	$2	$2			
Second Priority	Neutron correlation	Solid-state neutron detectors	$3	$3	$3	$3	$3	$3			
Third Priority	Neutron correlation	Large-area detectors—thermal	$2	$2	$2						
Third Priority	Gamma imaging	Mechanically collimated systems	$1	$1	$1						
Third Priority	Neutron imaging	Neutron imaging detectors	$1	$1	$1						
Third Priority	Neutron source	Radioactive source based	$5	$5	$5						
		Total	$81	$80	$80	$72	$72	$72	$36	$36	$36

three portfolio requirements to warrant inclusion as per the established criteria. These R&D areas may be of particular interest for individual users or across a narrow range of user ConOps, but they were not of wide enough utility to include in the prioritization.

Also included in Table 9 is the estimated target cost per year in millions of dollars and an estimate of the total time required to advance a technology area from its current level of maturity to a capability demonstration. The dollar figures provided are considered gross estimates only and were arrived at by the working group in a process completely unconstrained by and disassociated from the federal budget process. The dollar figures provided in the data tables assume level funding for each anticipated development year in FY2007 dollars, and thereby do not account for inflation or other cost escalations influencing the total effort to execute R&D at the national laboratories and facilities. In developing these estimates, there was no rigorous evaluation of cost conducted for a particular technology development path. Rather, a consensus estimate was arrived at by the working group to capture a rough-order estimate for the total development effort. Actual development costs may vary widely from these gross estimates.

Neither the cost estimate nor the time-to-develop parameter are considered as metrics in our prioritization, though they are not independent of maturity, risk, and impact, which are considered in prioritization. These cost and development time estimates are provided in the table as indications of the level of effort required to bring a particular technical solution to demonstration. It should be recognized, however, that there are large uncertainties associated with both.

Time-ordering of the R&D path, as is sometimes done in roadmapping exercises, has not been performed here. While there are dependencies among the technologies, as assumed in our archetypal systems development path per requirement, improvements in each technology class can individually have a positive benefit for the global nonproliferation regime independent of overall systems solutions. In addition, a highly structured R&D timeline that spans a decade is largely irrelevant given the uncertainty in budgets, scientific breakthroughs, and changing government priorities for nuclear nonproliferation. The anticipated value of this roadmap is instead to highlight the need for improvement in each high-impact technology, as quickly as possible and preferably in concert by providing a frame work for generating input for soliciting and selecting new proposals in these areas.

First-Priority R&D Areas

In the following paragraphs, additional details regarding required development directions for each of the highest-priority R&D paths are outlined.

Neutron/Gamma Correlation—timing, multiplicity, signatures: Developing robust, large solid-angle neutron and gamma counting detectors and associated detection algorithms, with nanosecond to microsecond timing capabilities, is ranked in the highest category, because there is a strong likelihood that time-correlated and multiplicity-related methods can provide important advances in our ability to detect, identify, and characterize SNM, and in particular HEU, even in the presence of shielding, in both active and passive scenarios. This is a unique signature and unmistakable as being derived from multiplying media. Moreover, these same techniques are likely to be useful against the two somewhat lower-priority requirements, so that the technology is cross-cutting and applicable across the program. R&D in this area is meant to encompass both the development of improved detectors and algorithms for correlated data analysis, as well as experimental and theoretical work on the underlying nuclear data related to correlations between multiplicity, energy, time and particle type (gamma/neutron). This latter aspect is highlighted as being unusual as well as important, since it is one of the few instances in the context of nonproliferation where further research into the underlying basic physics of the emitted particles can provide direct near-term benefit to detection applications.

- In the area of <u>time-correlated gamma-ray detection</u>, the main paths for research in the next 6–9 years are:
  - Developing fieldable devices capable of measuring nanosecond inter-event times with high absolute efficiency to facilitate time-correlated and multiplicity techniques. High absolute efficiency means that both solid-angle coverage and intrinsic efficiency must be substantial, so

that physically large (tens of centimeters linear dimension) detectors are advantageous. In 1–3 years, it is likely that a several-dozen channel pixilated gamma-ray counting system with nanosecond resolution will be available as demonstration devices. In 3–6 years, the development phase of this effort should turn to improving the fieldability and lowering the cost of such a system. In 6–9 years, with further development of timing detection algorithms, it is possible to imagine handheld devices with fissile radioisotope identification capabilities based on timing information rather than spectroscopy.

- In the area of neutron detection, we identify the following research directions:
  - Improved pulse-shape discriminating (PSD) detectors—The best PSD detector, stilbene, is expensive, limited in size, manufactured from toxic chemicals, and currently unavailable from U.S. vendors. Other options, such as xylene, have worse performance and are highly toxic liquids, and thus inconvenient for deployment. Research should be performed into developing alternative PSD detectors made of benign, preferably solid materials. The path for this research will be discussed in more detail in the materials roadmap.
  - Improved threshold neutron detectors—Excellent gamma-ray rejection and threshold capability has been achieved in commercial superheated liquid neutron detectors, for example. These detectors, however, operate in a dosimetric mode and are, thereby, not very useful in nonproliferation applications. R&D into improved threshold neutron detectors should continue to focus on the identification and exploitation of other methods that provide real-time data.

Neutron Correlation, large-area detectors—high energy: Large-volume (> ~m^3) liquid or solid combined gamma/neutron detectors. Low-cost, large solid-angle coverage detectors with fast-timing capability are useful for combined neutron and gamma counting, with or without discrimination by particle type and energy. Deficiencies in current detectors include, high-cost, low stopping power for MeV-energy gamma rays and neutrons (plastic and liquid scintillator), and toxicity, flammability, and temperature-dependent response (i.e., liquid scintillator). Research focus should be on non-toxic and non-flammable liquids or solids, addition of high-*Z* dopants to liquid or plastic to enhance stopping power for gamma detection or neutron absorbers for neutron detection without reducing light output or clarity, addition of neutron-capture additives to non-toxic liquids or to plastic detectors, and lower cost. Though cost is a consideration, plastics are preferable for ease of deployment, and three-year time scales may suffice to develop deployable systems.

Gamma Spectroscopy, high-resolution gamma-ray detectors: While a more complete examination of R&D in this area will be considered in the Advanced Materials roadmap, it is clear that higher-resolution portable and large solid-angle gamma detectors will be relevant for all three portfolio mission requirements. With significant investment from industry and government, routinely available, possibly low-cost, room-temperature spectroscopic capability at the level of 1% full-width half-maximum (FWHM) at 662 keV appears to be within reach in the next few years. This would allow better isotope identification capability, faster time to detect, and provide a richer data set in multiplicity and other analyses, making this a cross-cutting technology. Similarly, improved deployability for sub-1% resolution cryogenic detectors would also have cross-cutting impact.

- Within the gamma-ray spectroscopy category, the broad directions of future research are:
  - Material science research—Research into new radiation detection materials and the properties of existing detector materials is the subject of a separate NA-22 portfolio and roadmap. Additional research and development is needed into the most promising detection materials, including the lanthanum halides and cadmium zinc telluride (CZT), and into identifying and exploiting other promising materials. It should also be emphasized that improved spectroscopy comes not only from discovery and refinement of materials properties, but also from lower-noise electronics, improved collection of charge in the case of semiconductor detectors, improved collection of light in scintillator detectors, as well as more sophisticated algorithms for identifying isotopes.
  - Improved front-end/analog and trigger electronics—Front-end electronics refers generically to analog signal processing devices such as preamplifiers and PSDs, which condition signals prior to digitization. Preamplifier noise is mainly a function of the design of the front-end electronics. Recent improvements in complementary metal oxide silicon (CMOS) ASIC technology have made possible the design of metal-oxide semiconductor field-effect transistor (MOSFET)-based preamplifiers with significantly lower noise, lower power consumption, and smaller size than the current junction gate field-effect transistor (JFET) readouts. Borrowing from the example of coplanar grid (CPG) CZT detectors, development of custom ASIC preamplifiers would bring about a major improvement in detector performance, and would enable the assembly of large CPG arrays for use in spectroscopic portal monitors and high-efficiency imaging systems. This example points to a more general need for improved low-noise electronics readout, optimized for particular detection systems. A still more ambitious goal is to develop a generic set of low-cost, low-power, commercial off-the-shelf (COTS) analog electronics (with adjustable parameters) that could be used to accommodate a wide range of input signals and detector types. Trigger electronics refers to digital or analog hardware that is used to select a subset of raw data in real time according to preset conditions, such as energy thresholds or time-coincidence information. The new generation of field-programmable gate arrays, microprocessors, and other high-speed, on-board data processing software are beginning to be used as easily reconfigurable trigger hardware. Further research is needed into routine integration of these devices into portable detectors and testbeds. Eventually, small-size, low-power, flexible trigger electronics could replace the bulkier and higher-power NIM/VME/CAMAC standards that are now used in testbeds and in even in some deployed devices.

— Improved device fabrication techniques—In semiconductor detectors, electronic noise is due to the combined effects of detector leakage current and preamplifier noise. The fundamental factors that determine leakage current and its noise characteristics have not been fully investigated. Significant R&D is needed to study these in detail and to develop improved fabrication techniques that minimize detector-related noise.

— Improved photosensors for scintillation devices—The full energy resolution capability of scintillator detectors has not yet been achieved, in part because of imperfect collection and conversion of scintillation light. Research is needed into improved collection methods, such as optimized geometries or wavelength shifting coatings, as well as improved quantum efficiency of photomultiplier tubes (PMT), avalanche photodiodes (APD), and other light sensors. A factor of 2–3 improvement in resolution is possible by increasing PMT quantum efficiencies from their current ~20% levels to approach 100%. To improve deployability, further research is needed in the area of replacing the relatively delicate PMT, which is a vacuum device, with solid-state light conversion devices—while maintaining the good linearity and single photoelectron capabilities of the best PMTs. Investments in these areas are likely to be significant, and will require industry cooperation, but could rival the impact of a new material discovery.

— Improved data processing algorithms—Current commercial isotope identifiers suffer from false positive and false negative results in real-world searches. Some improvement in this area may come from research into more sophisticated data processing algorithms.

Neutron Source, accelerator based: Improved detection and identification of shielded HEU will require further development of neutron sources with a range of capabilities, including focusing, thermal and fast neutron energies, and ease of use in the field, up to and including small portable sources. Improved neutron sources will also be useful for detecting shielded plutonium and in standoff scenarios, so that the technology is relevant to all three requirements.

- D-D, D-T, and T-T interaction-based sources continue to dominate foreseeable accelerator neutron source development. Desired source properties include long-lifetime ion and accelerator sources, that require low power to operate, and intensities approaching 10^{12}–10^{15} neutrons per second. A further desire is to develop focused beams of neutrons.

Photon Source, broad spectrum and monoenergetic: Gamma sources, in particular high-brightness monoenergetic or bremsstrahlung sources, are also important to develop for next-generation detection applications, especially to increase detection confidence, identification specificity, and standoff capability. Further developing pulsed and continuous wave (CW) bremsstrahlung fixed-installation, transportable, or portable sources may enable entirely new classes of detection scenarios at fixed choke points (border crossings), maritime interdiction, perhaps limited search or contain situations, and other cooperative and non-cooperative monitoring applications. Accelerator-based bremsstrahlung sources are well understood and develop technologies that are now beginning to be further developed for field use. Lowering power consumptions, improving ruggedness, reliability, portability, and source lifetime—as well as more fully characterizing the emitted radiation field and stimulated signatures—are all areas of current investigation.

- Pulsed systems may be required to reduce sources of interfering background in active interrogation systems. Photon energies of interest span a wide range from a few MeV for exploitation of certain signatures (especially NRF) up to tens of MeV for detection at a distance and the stimulation of photofission. Pulsing rate needs range from tens of Hz to kHz and potentially beyond. Accessing this high-rate operation space may be initially limited by detector performance so that overall system improvements may await the introduction of more-capable detector systems. The usefulness of these systems in stimulating NRF signature is also being explored.
- Continuous photon sources capable of CW operation are of interest to exploit nuclear signatures such as NRF. The low rate of emission for NRF signatures is expected to require continuous, low-intensity stimulation to improve the excitation rate while maintaining a relatively low instantaneous induced background. To date, such sources have not been made available to field use. Studies are underway to evaluate the applicability of a wide variety of photon sources for detection applications that exploit the NRF signature.
- Monoenergetic sources are particularly important to the exploitation of NRF signatures by virtue of the reduced interference from extraneous off-resonance photons, and the potential of reducing radiation doses to the target and participants. The latter is made possible by concentrating interrogating radiation in a narrow band of energies near the very sharp resonance(s) and, thereby, eliminating intense radiation in all other spectral regions that are not effective in inducing the desired signature. Current expectations for energies of interest are in the 1–5 MeV range. Practical application, however, may be somewhat far off due to many challenging technical obstacles. The large size and high-power requirements of many of these sources, particularly monoenergetic sources, make it unlikely that there will be near-term successes. This potentially very impactful area of investigation will require a long-term commitment to development in order to realize any benefit for nonproliferation or counterterrorism applications.

Second-Priority R&D Areas

Neutron Imaging, 3D neutron tracking detector: Neutron imaging is a less-explored but nonetheless relatively low-risk area of research to which the second tier of priority is assigned. The technology is most appropriate for the shielded plutonium detection requirement, but may potentially have relevance for standoff detection in active scenarios as well. As with gamma imaging, significant research in this area has already been undertaken in the fundamental physics community (nuclear, high energy, and in the case of gamma-ray imaging, astrophysics), and can be adapted for nonproliferation purposes. One type of thermal neutron imaging device based on a coded-aperture, multi-anode ^{3}He chamber has been made available to nonproliferation applications, albeit with some development needed to enhance deployability. No fast neutron imaging devices have been thus far developed that are directly suitable for nonproliferation needs. The most fruitful lines of research in this area include:

- Light-gas time projection chambers. Directional neutron counting in 0.25 cubic meter scale light gas (^{4}He) time projection chambers (TPCs) has been demonstrated. It is expected that substantial additional development (on the order of 2 program cycles, or 6 years) is required to bring this technology to a fieldable capability. With this investment it may be possible to achieve light, portable, TPCs with alkane gas target media in carbon fiber vessels, having 10 degree pointing accuracy for a 10 incident neutron sample (better angular precision with higher counting statistics), 10% or better intrinsic efficiency, in cubic meter scale sizes. With further time and investment, it should be possible to develop ^{3}He TPCs, in which a few percent energy resolution is combined with one degree or better angular resolution while maintaining large size and portability. These performance targets are made possible in an absorber gas like ^{3}He since full kinematic event reconstruction is now possible by recording trajectories of entirely charged particle products. This full kinematic reconstruction allows for true event-by-event as opposed to stochastic pointing capability.
- Neutron scatter cameras. Neutron scatter cameras operate by recording individual fast neutron scattering interactions in at least two detection planes. Time of flight and pulse shape may also be recorded in order to reject gamma interactions and reconstruct incident neutron energy spectra. As with TPCs, comparably rapid development and similar specifications may be anticipated. Ten–twenty channel laboratory systems could be available within a year, and deployable square meter devices with hundreds of channels could be made available in 6 years. It is uncertain whether the intrinsic efficiency will be comparable to that of gas TPCs.

Gamma Imaging, electronically collimated system: Gamma-ray imagers are assigned to the second tier in prioritization as being somewhat more difficult to exploit in nonproliferation contexts than counting and spectroscopic approaches. Nonetheless, there are several important potential advances to be expected in this area, particularly related to standoff detection and improved time to detect, which merit further R&D. Forthcoming technology studies related particularly to gamma-ray imaging will be important in establishing the R&D trajectory for this suite of applications. One method of imaging—the electronically collimated systems or Compton camera approach—has also been developed over many years in astrophysics contexts, and are only now beginning to be explored for nonproliferation applications. Additional work is needed to reduce cost in these somewhat expensive multi-detector systems, increase detection efficiency, and further develop and refine event reconstruction algorithms specific to nonproliferation applications. As with imagining systems for other applications (e.g., medical imaging), low- or high-resolution detectors and detectors of varying sizes may be useful, depending on the ConOps.

Gamma Spectroscopy, algorithms for ID in active systems: There has to date been little effort applied in the area of algorithm development for extracting spectroscopic signatures of radioisotopes for systems that stimulate a response with an external source of radiation. Topics that may be of interest are the time domain nature of the signal unique to active interrogations systems, exploiting characteristic emissions from stimulated materials, and extending the energy range beyond the canonical 3 MeV range typical of intrinsic gamma emission.

Neutron Correlation, solid-state neutron detectors: Small-volume (< ~10 cm^3) solid-state detectors are desired for a variety of nonproliferation applications. Correcting the deficiencies in the existing standard neutron counter, ^3He, research in this area must focus on replacement of the pressurized gas volume with a more robust solid-state detector, make available low-cost, low-power and rugged operation, as well as high intrinsic efficiency for neutron detection, and demonstrate a path to 1–1,000 cm^3 volumes through tiling or large-area processing methods. A portable and reliable replacement for ^3He possessing few of the disadvantages with these systems will have a high impact on nonproliferation and nuclear security missions.

Third-Priority R&D Areas

Neutron Correlation, large-area detectors—thermal. Gas-filled thermal neutron detectors are considered a mature technology. As such, the development of a large-area thermal neutron detector is possible with currently available ^3He sensor technology. Enabling technology R&D into the development of an alternate capability like solid-state materials for thermal neutron detection is encouraged to increase field capability.

Gamma Imaging, mechanically collimated systems: The main focus in this class of detector should continue to be the relatively mature coded-aperture systems. These systems enjoy many advantages over simpler collimating systems like pinhole and Anger cameras, including greatly increased efficiency and field of view. Research should focus on lowering cost, improving deployability, and use of hybrid and active mask techniques to improve overall efficiency and reduce total system weight.

Neutron Imaging, neutron imaging detectors: Thermal neutron imaging detectors have been demonstrated in field tests. Further work is needed to develop robust fieldable devices and to integrate into active interrogation systems as appropriate.

Neutron Source, radioactive source-based: There is a long history of exploiting radioisotope sources in the nuclear and related industries for a variety of applications including gauging, material composition logging, and radiography.

Transportability and dose are the main challenges to using neutron sources in many nonproliferation applications that focus on material detection. Intense radiation sources should only be explored for field use when an induced signature in SNM is identified that is simulated by that particular radioisotope and when this approach offers some advantage over other detection or identification methods. To date, applications have been restricted to gamma radiography in very controlled situations (such as at border crossings) and the use of small alpha sources to generate neutrons for transportable neutron interrogation applications.

R&D Investment Strategy

The prioritization developed in the previous section (Prioritization Across Portfolio Requirements on page 53) for R&D technical classes across the three portfolio requirements identifies the highest-value R&D investment areas necessary to demonstrate the highest-impact new capabilities. This prioritization alone, however, does not provide a sufficient strategy to make R&D funding decisions. It is recognized that the target funding identified by the working group in their unconstrained estimates to more completely develop these technical areas is well beyond what is currently expected for this portfolio based on funding request planning. It is also important to note that the technology development effort identified by the working group in this document should be considered a shared responsibility among the broader interagency R&D community (identified in the Portfolio Requirements and the Roadmap Process on page 18) where technology need commonalities exist. Given these concerns, it is critical to establish a practicable methodology for selecting R&D investment directions. Considerations that are critical to making funding decisions include the status and distribution of currently funded R&D against the identified priorities, the current year budget for starting new R&D projects, the number and quality of proposals received in a particular proposal cycle, and the extent to which other agencies are funding complementary R&D across the community. This section establishes a methodology for balancing those considerations and arriving at a sound investment strategy.

Assessment of Current Portfolio

The current SNM Movement Detection mission-focused portfolio supports a wide array of R&D efforts. These are focused on both the R&D to realize new capabilities and on the maturation process necessary to demonstrate capabilities already beyond the concept phase. All eight of the major R&D technology areas that are currently represented in FY2007 projects are shown in **Figure 6**. The notable features in the current R&D project mix in the portfolio are that there is a large emphasis on high-resolution gamma-ray spectroscopy, and a rather balanced approach in some of the other important areas of radiation imaging, source development, and correlated signatures.

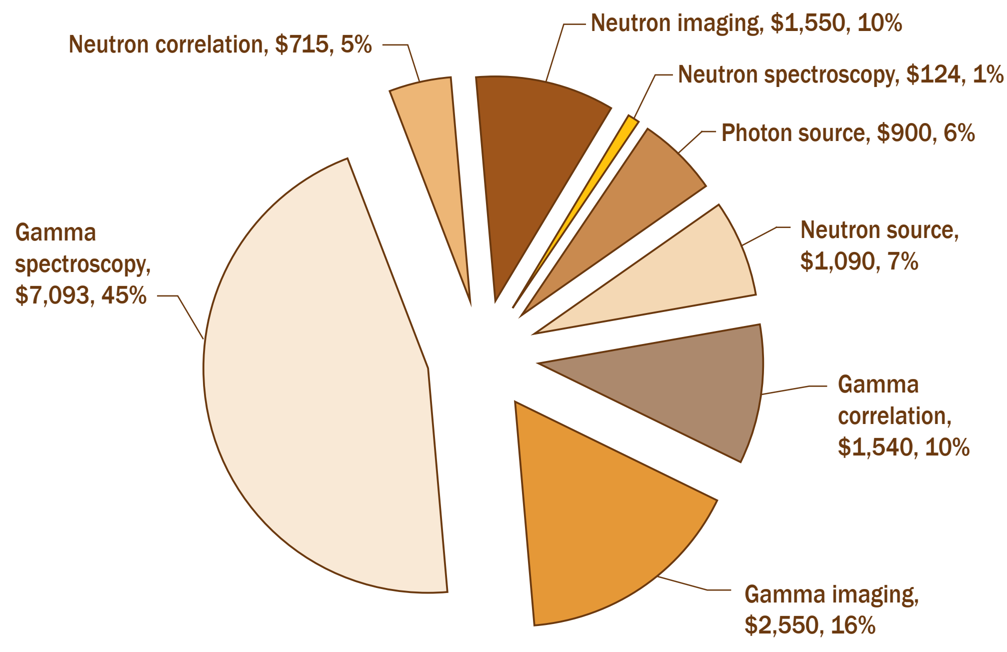

Figure 6. FY2007 allocation of funds in $K by R&D technology area.

A more detailed view of the portfolio at the R&D technology class level identifies a less-even balance of resource allocation. Several areas are currently not supported, notably including broad-spectrum photon sources and large-area energetic neutron detectors. These two R&D areas are identified in this roadmapping process as high priority, but have not been funded in the current portfolio because of lack in either sufficiently strong proposals or because the program is leveraging investment by other agencies in the federal government. Again it is clear from this figure that R&D for high-resolution gamma-ray detectors receives an appreciable fraction of total resources available. As noted elsewhere in this document, this R&D area has the most utility across the entire nonproliferation community and beyond to the entire national security and nuclear industry. While this R&D area's importance is not in question, its relative domination of the current portfolio makes an important example to be investigated further.

Applying the Roadmap

The task of applying the roadmap recommendations is an annual process that necessarily follows both the federal budget cycle and the proposal cycle of the NA-22 office. Applying the fiscal reality of limited resources for the program, it will be incumbent upon the program manager to select new R&D efforts to fund among potentially many tens to hundreds of highly ranked, medium-to-high priority proposals. In an environment where only a small fraction of the total budget is available for new R&D activities, it can be difficult to implement a broad strategic vision. The process described below is intended to be a guide that helps focus the portfolio in a direction that, with funds available, moves forward in the most efficient manor toward capability demonstration against the three portfolio requirements.

As the proposal cycle begins with the crafting of a solicitation for new R&D, this is the first opportunity to implement the recommendations from the roadmap into the project selection cycle. It is critical that the solicitation request proposals in area of need that align with the priorities of the portfolio defined in this roadmap. The selection of the most capable efforts from among the responses fills out the program and pushed technology development to fill the identified gaps. The process of solicitation and proposal selection should address the recognition of cohesiveness in the program and the spirit of advancement of technology thrust directions to arrive at an ultimate goal of capability improvement. Indeed, an effective program is not simply a collection of disconnected projects, but rather an interrelated set of complementary technology progression tasks focused by the overarching program goals (or mission requirements in this case).

The methods used to select new efforts from among the received proposals assumes that all proposals are reviewed both externally and internally and ranked for technical merit, programmatic relevance in our diverse user base, and sound management practices. It is assumed in this discussion that only high-quality proposals are considered for funding and that the program manager, beset with more proposals than available funds, must decide between several such proposals for distribution of limited resources.

Sound management practices on the part of both the executing laboratory and the NA-22 program staff are critical, both in the proposal preparation/selection process and in the project management thereafter. NA-22 program management will continue to rely on the laboratory program management to assist in the execution of office program objectives, including advancing the policies and guidance set forth in this roadmap. Since there are often many more internal responses at the laboratories to solicitations than proposals received by NA-22, the responsibility for successful program execution is shared. The laboratory program management is expected to put forward those project proposals that are in the best interest in advancing the program. NA-22 program management is expected to offer a fair, impartial, objective, and transparent review processes that shares information and rationale from the decision making process. Once individual R&D efforts are begun, program management at both the laboratories and NA-22 share in the responsibility for successful execution.

It should also be noted that scientific breakthroughs cannot be scheduled. This engenders the concept of risk acceptance or tolerance. A long-term R&D program such as this one is expected to take risks and push the envelope of capability.

It must be accepted that this entails potential degrees of failure, progress termination in technical dead-ends, project rescoping, down-selections, and the identification of new avenues of pursuit. A prudent approach would suggest careful prioritization, establishing clear project goals and expectations, and where funds permit, pursuing multiple technical paths to the same end. Risk management and mitigation constitutes an underlying theme.

The process outlined below is notional and is provided as an illustration only. It is realized that no process can prescribe an optimal outcome for all instances, especially where R&D efforts are concerned. The process for ranking proposals must first determine within which R&D technical class(es) a particular proposal is assigned. The proposals should then bin with other proposals in the same technical class for comparison. Direct comparison is an effective method in determining the most promising path(s) forward, as well as being an effective mechanism for assessing the individual attributes in a given approach. It is the review process, to include technical merit, management soundness, and programmatic relevance, that identifies position or rank order of proposals within a technical class. Rank ordering among technology classes is more challenging of course, and constitutes motivation for the roadmap. This ranking may be determined by assessing the degree to which each technology class is represented in the currently funded portfolio. The level of representation can be determined either relative to the total funding in the portfolio or relative to the recommended target funding levels in this document. The former biases the rank toward R&D that currently has small relative share of the funds available. The latter biases the rank toward R&D that is receiving proportionally less than recommended in this document, and will further bias toward technology classes that have more costly development paths. Both methods give higher ranks to proposals that appear in under represented technology areas. Selection between priority classes should favor those in the next higher class, i.e., those in the first-priority class should be ranked higher than those in the second-priority class.

A significant concern in applying either methodology described above is that blind adherence to a strict set of rules could result in a situation where limited funds could be spread too thinly across the supported R&D areas to realize any new capability in a reasonable time frame. It is recognized that in order to enhance capability in any given R&D area in a specified time frame, sufficient funds must be invested. This may force situations where certain technical areas receive no development investment for substantial periods.

In **Table 10**, the target funds per year and number of years anticipated to achieve significant progress toward capability demonstration has been shown for the highest priority level technical classes, and helps illustrate an example of favoring an R&D area in a situation where funds are limited. The current portfolio emphasis on R&D for high-resolution gamma-ray spectrometers, for example, consumes 46% of the FY2007 portfolio funding (**Figure 7**), yet it should also be noted that the FY2007 funding level of $7 million is 30% less than the recommended target funding amount of $10 million. This R&D effort would be considerably less successful if resources were diverted to balance investment across all high-priority areas. In such cases, the program is forced to make difficult choices on funds allocation, the balance to be struck being between funding an under-represented R&D area or building critical mass in a high-priority area.

A hypothetical example illustrating the ranking and selection process is illustrated in Table 10. In this example, the portfolio has $1.0 million for new projects in FY2008 and has received high technically ranked proposals in several areas. It is assumed that proposals were received in many R&D areas and that, when reviewed, these proposals were of insufficient quality for inclusion in ranking leaving several areas unrepresented. The rank of highly qualified proposals is performed by considering the FY2007 level of representation for each R&D area when compared with the recommended target funding levels established by the working group, and projects are selected from among those areas with least representation and highest priority. In this analysis it was determined that the R&D areas of large-area high-energy neutron detectors and solid-state neutron detectors were the most under-represented of the proposals received. In each

Table 10. Hypothetical funding process for new projects in FY2008 given highly ranked proposals in indicated R&D technology class.

				FY2007	FY2008	
Funding Priority	R&D Technical Area	R&D Technology Class	Budget ($M)	$14.2	$15.0	Hypothetical FY2008 Funding of New Projects
			Obligations ($M)		$14.0	
			New Starts ($M)		$1.0	
				FY2007 Funding	% Currently Funded 07	
Fund first ~2/3	Neutron correlation	Neutron detection—timing, multiplicity, signatures		$0.7	24%	
	Neutron correlation	Large-area detectors—high energy		$0.0	0%	$0.6
	Gamma spectroscopy	High-resolution gamma-ray detectors		$7.1	71%	
	Gamma correlation	Gamma detection—timing, multiplicity, signatures		$1.5	51%	
	Neutron source	Accelerator based		$1.1	14%	
	Photon source	Broad spectrum		$0.0	0%	
	Photon source	Monoenergetic		$0.9	5%	
Fund second ~1/3	Neutron imaging	3D neutron tracking detector		$1.4	47%	
	Gamma imaging	Electronically collimated system		$0.4	4%	
	Gamma spectroscopy	Algorithms for ID in active systems		$0.0	0%	
	Neutron correlation	Solid-state Neutron detectors		$0.0	0%	$0.4
Fund third -if user interest	Neutron correlation	Large-area detectors—thermal		$0.0	0%	
	Gamma imaging	Mechanically collimated systems		$0.9	90%	
	Neutron imaging	Neutron imaging detectors		$0.2	15%	
	Neutron source	Radioactive source based		$0.0	0%	
			Total Funding	$14.2		$1.0

Comprehensive Technology Development Roadmap

of these R&D technology classes, several proposals were received. It was then incumbent upon the process to establish rankings based on the technical review, relative risk, and potential return to select between proposals in the same technology class. Two proposals, one in each R&D technology class, were selected for a total new expenditure of $1.0 million.

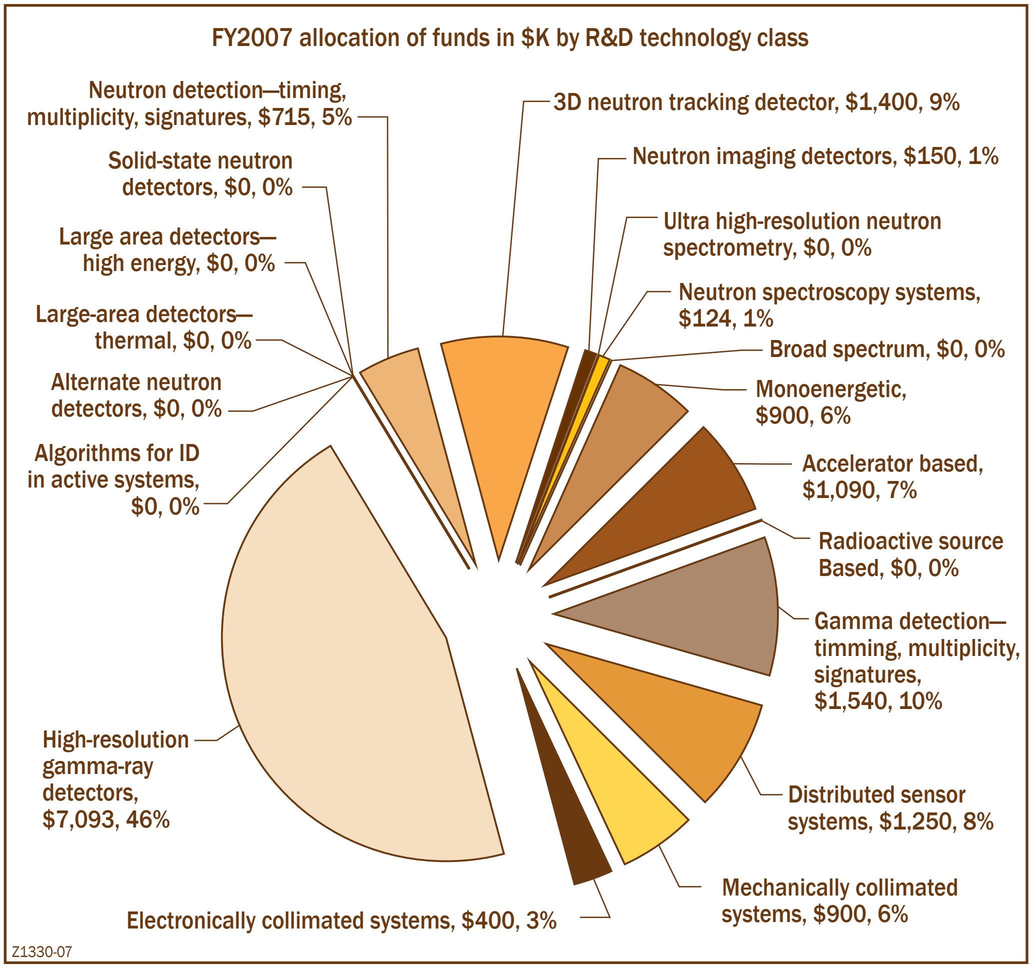

Figure 7. FY2007 allocation of funds in $K by R&D technology class.

Appendix A: Technology Overview

Appendix A: Technology Overview

Neutron Counting Overview

To facilitate the discussion of neutron counting in the context of special nuclear materials (SNM) detection, it is useful to categorize neutrons according to their kinetic energy. A reasonable barrier separating a high- and low-energy groups is 100 keV. *Fast neutrons* are defined, for the purposes of this document, as neutrons possessing energies above 100 keV, and thus able to penetrate substantial thicknesses of many materials, especially high-*Z* materials. *Slow neutrons*, on the other hand, possess much less in the way of kinetic energy, sub-100 keV, for our purposes, and can be absorbed in many materials, including low-*Z* materials and SNM. It should be carefully noted that these definitions are adopted to aid in discussion of neutron detection in this text and are functionally different than those employed in other related disciplines, such as nuclear reactor engineering. While 100 keV is not a hard barrier for a physical process that affects detection, detector design and function are substantially different in extremes above and below this separation point. Fast neutrons at high energies are most efficiently detected in scattering or “knock-on” interactions that liberate charged particles. Whereas, slow or low-energy neutrons are more effectively detected in absorption or capture reactions which liberate the detectable charged particles.

Neutron background in the environment at any energy is relatively small, about 0.005 background neutrons per square centimeter per second at sea level. Since SNM isotopes undergo both spontaneous and induced fission (which emits neutrons), the mere presence of an intense localized neutron source is an indication of a threat. Fast neutrons are of particular interest for SNM detection because fission neutrons emitted by SNM have a mean energy of about 2 MeV, but even slow neutrons can serve as an important indicator of the presence of SNM when the spontaneous fission rate is high as it is for plutonium. This, unfortunately, is not the case for pure ^{235}U. In practice, nonproliferation applications require the detection of both fast and slow neutrons.

Important selection criteria for counting detectors for fast or slow neutrons therefore include:

- Specificity for fast or slow neutrons. As a practical matter, identifying both fast and slow neutrons is rarely accomplished with the same instrument because the interaction mechanisms (scattering vs. absorption) are different. In some cases, fast neutrons are slowed or moderated by hydrogenous material surrounding a slow-neutron-specific detector.
- Large-area coverage to increase the gross count rate.
- High intrinsic efficiency for slow or fast neutrons.
- Insensitivity to gamma rays.
- Low cost.

An important additional criterion for neutron counters arises from the possibility of exploiting the *time* characteristics or signature of neutrons emitted by plutonium and highly enriched uranium (HEU). SNM emits time-correlated bursts of neutrons with characteristic time scales ranging from one nanosecond up to tens of microseconds. Even when average neutron rates from a fissile source are comparable to backgrounds, fluctuations in the arrival times of successive neutrons on nanosecond to tens of microsecond time scales can reveal a wealth of information about the material mass, isotopics, and, perhaps, shape. Because these neutrons can be captured in and scatter on surrounding materials, the time structure may also convey information about the surrounding materials. This approach adds another important criterion for neutron counting:

- Time-resolving capability at the nanosecond to microsecond level.

Finally, certain scintillating detectors discriminate between fast neutrons and gamma rays by measuring the difference in the time development of their electrical pulses. In the context of neutron counting, the purpose of these detectors is to unambiguously identify and count fast MeV-scale neutrons, which characterize fission, compared to the more copious gamma-ray backgrounds. (Energy information can also be obtained with these detectors, as discussed in the section on neutron spectroscopy.) This leads to a further criterion:

- 1 part per tens to hundreds of thousands or better neutron/gamma PSD capabilities in fast neutron detectors.

Current Examples of Neutron Counting Detectors

For slow/thermal neutron counting, ^{3}He detectors and BF_3 detectors are currently used. ^{3}He detectors are the most commonly employed detectors in nuclear search and monitoring applications, but suffer from the need for pressurized operation and relatively high cost. Their response and recovery times following a neutron signal are limited to microseconds, so that they are suitable for some but not all multiplicity counting methods, and perhaps only some active interrogation applications.

For fast neutron counting, plastic or liquid organic scintillator detectors are the most commonly employed. Plastic and liquid scintillators can also be used as crude measures of neutron energy distributions, and can have excellent (few nanosecond to hundreds of picoseconds) response and recovery time. They can also be used for fast neutron multiplicity counting. When doped with neutron capture agents like ^{10}B or ^{6}Li, for example, they can be made sensitive to slow neutrons. Organic scintillators have the further advantage of being relatively low in cost. Some of the liquid versions are toxic and flammable, however, and their light output can be affected by temperature variations at the level of a percent per Celsius degree making them somewhat difficult to use as field deployable detectors. Stilbene is a unique (and expensive) solid organic scintillator that has excellent PSD capabilities, a property that is more frequently found in the liquid-state organic scintillators. Yet, its manufacture involves the use of some highly toxic and carcinogenic materials.

Current R&D for Neutron Counting

In considering the performance criteria mentioned above, a suite of R&D activities are being pursued by NA-22 and others in the area of neutron counting.

The main lines of relevant research presently pursued are:

- **Solid-state inorganic neutron detectors:** These detectors are based on neutron capture agents such as boron or lithium, placed in intimate contact with semiconductor or other materials that are sensitive to the alpha particles emitted in the capture process. These detectors could have the advantage of being easier to deploy than current pressurized gas-based (^{3}He) neutron counters. Other areas in development are intrinsic semiconductor-based neutron detectors that consist of materials that contain elements with high cross-sections for neutron capture, such as boron nitride, are attractive due to their solid-state properties, have reduced weight, and exhibit potential for development into 2D flat panel arrays. These systems can sometimes be adapted to Si read-out electronics. Fast, gamma-insensitive semiconductor detectors such as SiC are being developed as fast neutron detectors for active interrogation systems. These detectors can operate in intense radiation fields and have been shown to be capable of neutron-photon discrimination through the utilization of pulse-shape discrimination techniques.
- **Threshold neutron detectors:** Some low-density solids and liquids can be made to act as threshold neutron detectors, in which super-heated liquid boiling and therefore detection can occur only if the neutron energy is above a certain level. This threshold capability provides direct sensitivity to the fast MeV-scale neutrons that are characteristic of plutonium, along with insensitivity to gamma rays and low-energy neutrons. Current detectors are, however, only dosimetric in nature, reading out only total neutron exposure following irradiation. Current R&D is focused on developing real-time methods for recording signals in these detectors, to facilitate their use to search applications.
- **Plastic scintillator, or non-toxic and non-flammable liquid scintillators:** These enable mixed gamma/neutron counting at relatively low cost and environmental burden. In some cases, these scintillators are themselves doped with neutron capture agents to provide or enhance sensitivity to thermal neutrons.
- **Water Cerenkov detectors:** High-efficiency, large-volume, and low-cost detection of neutrons may be possible through the use of water Cerenkov detectors doped with trace quantities of neutron capture agents. This technique relies on the photodetection of Cerenkov radiation created by neutron-induced reactions in neutron absorber doped water and has been demonstrated in basic physics experiments, using boron as a dopant. Other dopants like $GdCl_3$ have also been proposed.
- **Improved pulse-shape discrimination:** Current research is focused on new materials that may have PSD characteristics comparable to the best existing PSD detector, stilbene, but which can be grown or manufactured with larger size and/or lower cost than this difficult to obtain and hazardous material.

Appendix A: Technology Overview

Neutron Counting R&D Shortfalls

Current research efforts for thermal neutron counting are to a significant extent appropriate to the problem at hand. However, there is a shortfall in the area of detector systems sensitive over the entire neutron energy range, from several MeV (fission range) to well below the slow neutron range (< 100 keV) and into thermal energy range (~1/40 eV), of possible neutrons encountered in the field. Among the technologies listed above, only option 3 (neutron capture agent doped scintillator) appears likely to allow simultaneous detection and discrimination between fast and slow neutrons in a single detector.

Neutron Spectroscopy Overview

Neutron spectroscopic systems measure the energy distribution of detected neutrons. Direct measurement of neutron spectra in field systems is rare. Most currently employed systems infer the neutron spectra by moderating (slowing) high-energy neutrons to thermal energies for detection in a slow neutron detector and then applying complex statistical unfolding algorithms to determine a crude neutron spectrum. The process of both collecting and analyzing these spectra can be time consuming because of the need to acquire several statistically significant measurements over a range of moderating conditions. The programmatic concern surrounding neutron spectroscopy is in its usefulness for the unique identification of SNM. The energy spectrum of neutrons emitted by SNM is rather broad and generally featureless unless surrounded by materials that preferentially absorb neutrons only at specific energies. **Figure A1** shows the spectrum from pure plutonium (black trace), plutonium oxide (white trace), and shielded plutonium oxide (red trace). Distinct spectroscopic structure or features are apparent only in the oxide form (shielded or unshielded), due to absorption of neutrons in the oxygen.

For the purpose of simple identification of SNM, detailed neutron spectroscopy is normally not needed. However, neutron spectroscopy can be useful to

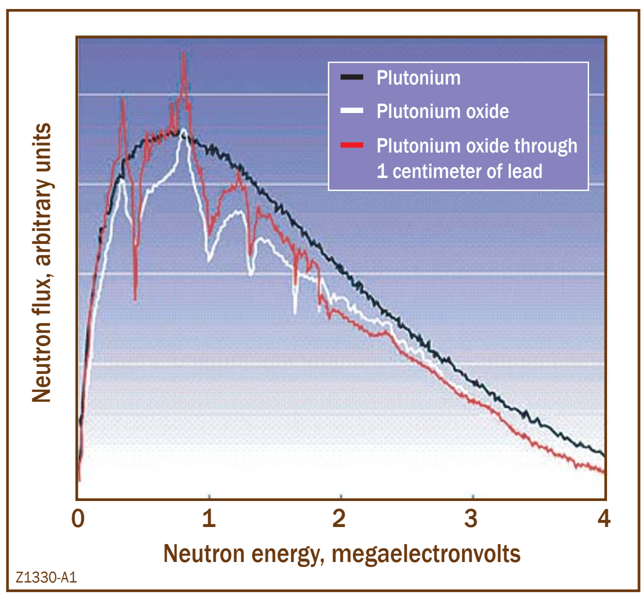

Figure A1. Example neutron energy spectra of plutonium, plutonium oxide, and shielded plutonium oxide.

characterize SNM and surrounding materials. Applications of interest include verifying the physical form of declared materials in the context of an arms control or safeguards regime.

Current Examples of Neutron Spectroscopy Detectors

Some contemporary examples of neutron spectroscopic detectors are:

- Liquid scintillator recoil detectors;
- Gas proportional detectors; and
- Variable shield spectrometers ("Bonner spheres.")

Current R&D for Neutron Spectroscopy

- **Microcalorimetry:** Research is now being conducted exploring neutron spectroscopy with superconducting transition edge detectors. These devices have very high resolution, but are limited in size and hence overall efficiency by the heat conducting properties of the neutron absorbing elements they contain. Attempts to circumvent this shortfall by multiplexing large arrays of such sensors are now being pursued.
- **Threshold neutron detection:** Very simple and crude neutron spectroscopy is being accomplished in threshold neutron detectors that sense neutrons above a specific reaction energy threshold. This has been previously discussed in the above section on neutron counting.
- **Pulse-shape discrimination:** Utilize shape discrimination of the electrical pulses from a detector to determine neutron energy in a neutron-sensitive liquid scintillator. This has also been previously discussed in the above section on neutron counting.

Neutron Spectroscopy Shortfalls

In the case of neutron spectroscopy, there are presently no detectors that combine high resolution with high efficiency.

In plastic and liquid organic scintillator recoil neutron spectrometers, only a few of the multiple interactions of a single neutron in the medium are registered, resulting in a loss of energy resolution. This occurs in part because the incident neutron energy can drop below the detectable recoil threshold after only one or a few scatters, so that some of the energy information is lost, and in part because the mean free path for neutrons in these media—tens of centimeters—are often longer than the typical dimensions of the detector, so that neutrons can escape the detector without depositing all of their energy there. Both effects combine to degrade the energy resolution of organic scintillators. To improve resolution, lower-energy threshold, fast-neutron spectrometers are needed, with detectable recoil energies extending down to several tens of keV energy range.

Properly instrumented, ^3He gas-filled detectors can be used as fast neutron spectrometers, with full reconstruction of the incident neutron energy following capture, if the final state triton and proton reaction product energies can be measured. In theory, this is far superior to a recoil measurement, since the full energy of the incident neutron can be recorded. There is currently little effort at practical implementation of this approach.

Neutron Imaging and Directionality Overview

Neutron imaging and directionality can be accomplished for either fast or thermal neutrons. Imaging neutrons refers to the creation of a 2D or 3D map of the location of neutron-emitting sources. The closely related concept of neutron directionality refers to identification of vector pointing to a neutron source, and is used to describe implementations in which there are insufficient statistics for creation of a true image. Both imaging and directional detection of neutrons may be useful for search and monitoring applications. Imaging and directional detection can help screen out the neutron background not arising from the direction of the threat source, and can reduce the detection time needed for localizing a source. Example applications for neutron imaging include measurements of the location of deposits of plutonium within process piping and equipment at a reprocessing facility, monitoring the locations of plutonium bearing drums in a plutonium storage facility, or searching for a loose source in a limited search area.

Industrial neutron imaging relies on the availability of intense neutron sources and detection of these neutrons by a position sensitive detector. Commercial systems depend on a high rate of neutron flux in order to create images, and are therefore not always directly applicable to the passive detection of SNM.

Current Examples of Neutron Imaging Detectors

No current commercially available detectors are directly relevant to passive neutron imaging of SNM.

Current R&D for Neutron Imaging and Directionality

Though not commercially available, a range of neutron imaging techniques has been examined in various research contexts, including:

- Scatter cameras;
- Coded-aperture imaging of neutrons;
- Occluded arrays;
- Collimated detectors; and
- Gas-based time projection chambers (TPCs).

The underlying technologies are analogous in many respects to gamma-ray imaging systems discussed below. Examples of current R&D for improved passive neutron imaging for plutonium detection include:

- **Time projection chambers:** Light gas-based (H or He) TPCs have been used for many years in the high-energy and particle physics communities to detect and characterize products of exotic, high-energy particle reactions. Current R&D is focused on converting these large and complex, high-energy physics experiment detectors into practical fieldable detectors for nuclear search and monitoring applications.
- **Liquid or plastic scintillator-based scatter cameras:** Neutron scatter cameras represent another approach to measuring the direction of MeV-scale neutrons. Scatter cameras reconstruct the direction of incident neutrons by observing two (or more) successive scattering interactions from the same neutron in spatially separated layers of pixilated, neutron-sensitive sensor arrays. The absolute and relative energy depositions in two detector pixels constrain the energy and angle of incidence of the incident neutron. Several pixel systems have been demonstrated in the laboratory by several researcher groups. Current R&D is focused on methods to efficiently manufacture and utilize relatively large-area (square meter) neutron pixel devices that can be field deployed.
- **Thermal neutron imaging:** Very low-energy neutrons can also be imaged. Though they are of relatively low energy, they are still able to traverse many tens of meters in air before losing directional information. Current research is focused on coded-aperture imaging using position-sensitive ^{3}He proportional counters. It should be noted that neutron images formed by this technique are more indicative of the material that slows or moderates the neutrons rather than the source of SNM-emitting neutrons. It is, therefore, of limited applicability.

Neutron Imaging and Directionality Shortfalls

Overall, less R&D effort has been placed into neutron imaging and directionality than in the corresponding techniques for gamma-rays. This is in part due to the fact that astrophysics has been a strong driver for gamma-ray imaging techniques, while there are fewer corresponding academic or industrial drivers for neutron imaging. This is unfortunate, because in the case of plutonium with its relatively strong neutron output, neutron imaging can be a powerful detection and localization tool. For scintillator-based scatter cameras, the main difficulties arise in increasing the number of pixels, lowering the cost per channel, and increasing the detection efficiency per pixel. For gas TPCs, fragile wire readouts need to be replaced with more mechanically robust Gas Electron Multipliers, Large Electron Multipliers, or other such devices. Current detector systems are often heavy, predominantly because steel pressure vessels are the simplest choice for containment. Research is also needed into carbon fiber or other lightweight chambers to facilitate field deployment. Finally, there are several possibilities for the choice of detection gases in TPC detectors. Hydrogen and the alkane molecules are promising candidates for elastic recoil-based imaging, while absorption reactions in ^{3}He could allow for full kinematical reconstruction of the incident neutron direction and energy even by event, at the cost of reduced efficiency. For both types of fast neutron imaging, these problems are being incrementally addressed in existing R&D efforts. In the area of thermal neutron imaging, coded-aperture systems would benefit from improvements in solid-state thermal neutron detectors, which might replace the ^{3}He pixels now in use.

Gamma-Ray Counting Overview

Gamma-ray counting detectors are principally used to determine the presence of radioactive materials. Due to the rather simple requirement placed on these systems of registering a gamma interaction in the detector without a precise measurement of the energy or direction of the incident gamma, they are low cost, and commercially available in sizes ranging from handheld pagers to drive-through portal monitors. Crude location information is possible to extract with these systems through so-called “proximity imaging,” in which changes in the count rate or intensity measured by the detector is used to indicate the proximity of a radioactive source.

Current Examples of Gamma-Ray Counting Detectors

Gamma-ray counting detectors are rather simple devices in principle that record either light (scintillation) pulses in plastic or alkali-halide crystalline scintillator materials, or electric pulses resulting from gas ionization as gamma rays interact via photoelectric or Compton interactions in the detector. There is along history of development of these detectors, and accordingly, a long list of gamma-ray counting detectors. Prominent examples include:

- Ionization chambers;
- Proportional counters;
- Geiger counters;
- Plastic scintillators; and
- Thallium-doped sodium iodide [NaI(Tl)] or cesium iodide [CsI(Tl)]

These detector types are in widespread industrial, medical, research, and national security use. The scope and variety are large with many having niche applications as far reaching as nuclear reactor operation monitoring, to personnel dosimetry, to research-quality radiation spectroscopy. An exhaustive review is beyond the scope of this effort.

Current R&D for Gamma-Ray Counting

More advanced gamma-ray counting techniques are beginning to be considered in the context of time-correlated measurements for detection of shield plutonium and HEU. The detection signal generated in plastic and liquid scintillators due to a gamma (or neutron) interactions is intrinsically fast in these materials, ranging from hundreds of picoseconds to nanoseconds. In this perspective, the materials science of these detectors is relatively mature so that materials research is not the main concern. Instead, the collection speed of the readout electronics is currently driving important advances in this area. High-speed, low-cost, multichannel waveform digitization has become available in the past 5–10 years. These digitizers are now being incorporated into test systems, opening the door to significant improvements in our ability to extract timing information from gamma-rays emitted by fissile material.

A second important area of recent research interest is in improvement of the PSD capabilities of combined gamma/neutron detectors. Current capabilities allow discrimination between fast neutrons and gammas at the part per thousand level, for recoil energies above about 250–500 keV. Order of magnitude improvements in this rejection capability are being sought through the use of new materials, and through more-sophisticated algorithms for extracting pulse-shape information from existing materials. As with straight gamma counting detectors, improvements in waveform digitization speeds will facilitate the development and use of such algorithms, as will the development of faster on-board computing capability.

Gamma-Ray Counting R&D Shortfalls

While some success has been achieved in improving gamma/neutron discrimination capability, and increasing the time resolution of detectors, additional effort is needed to move these systems from the laboratory to the field. Lighter-weight and lower-cost digitizers, perhaps implemented on application-specific integrated circuits (ASICS), would help enable truly portable devices with high-speed counting capability.

In terms of efficiency improvements, it is possible that benefit may derive from the increased stopping power that can be achieved in plastic or other scintillators when doped with high-*Z* materials. In principle, this increases the photopeak-to-Compton ratio and improves the ability to identify specific radioisotopes. Although commercial vendors now advertise such scintillator formulations, laboratory investigations have shown that light-collection efficiency is significantly degraded. Because of this use is not widespread, and further research is needed to evaluate the actual benefits of high-*Z* doping.

Appendix A: Technology Overview

Gamma-Ray Spectroscopy Overview

Gamma-ray spectroscopy is an essential tool for both identification and characterization of SNM, and in fact radioactive materials in general. Most spectroscopic detectors (aside from superconducting detectors) fall into two main categories: semiconductor detectors and scintillator detectors. These detect, respectively, ionization and scintillation signals, with the induced signal in both cases being proportional to the energy deposited by the incident gamma ray. The principal figure of merit for spectroscopic detectors is energy resolution, often expressed as the percentage of the width of the photopeak (100 × [FWHM/Peak Energy]) for the 662 keV peak of the isotope ^{137}Cs. Currently available spectroscopic detectors trade off other desirable features, such as detection efficiency, cost, and fieldability against this figure of merit. Semiconductor detectors generally have the highest resolution in practical devices. In particular, cryogenically cooled high-purity germanium (HPGe) detectors have the highest energy resolution of any off-the-shelf spectroscopic detectors, about 0.15–0.30% at 662 keV. Historically cooling has been accomplished using liquid nitrogen as a passive refrigerant, severely restricting the deployability of HPGe. Recent strides in the development of mechanical refrigeration have made it possible to eliminate liquid nitrogen and have enabled commercial off-the-shelf field-deployable detectors.

Room-temperature scintillating and semiconductor detectors are generally lower cost than HPGe, but have poorer resolution, ranging from about 1–3% for the semiconductor detector CZT, with the higher value typical of most commercially available devices, to 7–8% for the scintillator detectors thallium-doped CsI(Tl) and NaI(Tl). New lanthanum halide scintillator-based detectors ($LaCl_3$ and $LaBr_3$) are emerging on the commercial detector scene. These devices have resolution on the order of 3–4% but are much more expensive than their alkali-halide counterparts. Additional research to improve the yield of these crystalline materials can help improve price-performance.

Commercial gamma-ray spectrometers are often equipped with radioisotope identifier (RIID) software, which attempts to identify the observed radioisotopes in an automated fashion by comparing the measured spectrum with a library of known spectra. Some of these devices provide a ranked list of candidate isotopes, and may be self-calibrated with built in check-sources. The current generation of commercial RIID software and algorithms produce very poor identification results when tested in realistic field environments. There is much room for improvement in this area.

Current Classes & Examples of Spectroscopic Gamma-Ray Spectrometers

- Very-low energy resolution—(20–30% FWHM): Plastic scintillators like PVT (polyvinyl toluene) are relatively inexpensive and easy to fabricate in large dimensions. As such, this material makes up the active detection medium in the majority of very-large radiation screening equipment, like portal monitors. Since it can be made in large sizes and has reasonable stopping power for gamma rays of interest, detectors made from this material have rather high efficiency and are capable of detecting relatively small quantities of radioactive materials. The very poor energy resolution, however, renders PVT largely ineffectual as a radioisotope identifier. Some attempts are made at gross energy binning or windowing, resulting in a limited ability to categorize materials as threat or benign.

- Low energy resolution (6–10% FWHM): Typified by NaI(Tl) or CsI(Tl), these RIIDs are used to enhance detectability in counting applications by applying low-resolution spectral information. They also have moderate characterization capability and are relatively inexpensive and commercially available in sizes up to a square meter. These materials have been extensively employed in small handheld and portable devices including backpacks and vehicle-mounted and road-side monitors. Current R&D is focused on developing higher-resolution replacements to these materials. Though the emerging higher-resolution materials are showing great promise and beginning to find niche field applications, they are currently still too small and expensive to represent a viable replacement for NaI and CsI. Even as these higher-performing emerging materials become more readily accessible, it is expected that there will remain many applications where only medium-resolution is required and NaI, CsI continue to play an important role. In fact, over the past several years, a Department of Homeland Security initiative to develop Advanced Spectroscopic Portal (ASP) monitors has resulted in the development and deployment of hybrid portal monitors. These monitors continue measure gross count rates above a prescribed intensity threshold, but also incorporate spectral analysis algorithm. This capability is enabled by replacing low-resolution plastic detectors with large NaI(Tl) or other medium-resolution detectors.
- Medium energy resolution (1–3% FWHM): Typified by the emerging materials lanthanum bromide [$LaBr_3$(Ce)] and CZT, these RIIDs are generally employed in small systems used to perform identification. CZT is also used in some "pocket-pager" applications. This is a relatively new class of materials that can provide most of the benefits of the high spectral resolution systems while operating at room temperature. These systems are considerably more expensive than the preceding types and have limited commercial availability. They are also not yet commercially available in the sizes desired for some applications or at a reasonable cost to allow wide spread use. They may also require sophisticated electronics and readout algorithms to enable all of the detection benefit.
- High energy resolution (0.15–0.3% FWHM): HPGe is the only practical example in this category, though some of the emerging medium-resolution materials (especially CZT) are being further developed to improve resolutions and may one day compete with HPGe in some applications. HPGe detectors tend to be used in small- to medium-sized detection systems that are capable of detailed spectral characterization where high-confidence radioisotope identification is required. The sensor element (HPGe single crystal) in these systems must be kept at liquid nitrogen temperatures in order to function effectively at high spectroscopic

resolution. They compare in cost per unit volume to some the medium-resolution systems, but are much more readily available commercially in significantly larger sizes up to those required in large, man-portable or vehicle-mounted systems.

- Ultra-high energy resolution (0.01–0.1%): Detectors based on superconducting transition edge sensors functioning as micro-calorimeters have been laboratory demonstrated at resolution as high as 0.025% at 100 keV. They rely on the heat captured in an absorber (e.g., Sn) by gamma (or neutron or alpha) interactions to elevate a superconducting junction (e.g., Mo-Cu) above its transition temperature. Like HPGe, these sensors must be cryogenically operated, and are currently limited to sub-millimeter sizes in most cases, relegating them to laboratory sample analysis applications. Their main function for nonproliferation is in the area of nuclear forensics and safeguards.

Current R&D for Gamma-Ray Spectroscopy

Current R&D for gamma-ray spectroscopy applications includes several critical development directions:

- Development of new medium to high-resolution spectroscopic-quality radiation detection materials;
- Improved charge collection and fabrication techniques for semiconductor detectors;
- Improved light collection and fabrication processes for scintillator detectors;
- Lower noise and lower power readout systems;
- Faster post-processing of signals;
- Improved RIID capability; and
- Improved fieldability.

The effort invested in the search, discovery, and characterization of new radiation detection materials is significant, and is considered separately in more detail in the forthcoming materials roadmap. In addition to tests of promising materials, some recent materials research has focused on the ability to *predict* bulk properties of materials relevant to spectroscopy, using quantum mechanical or other first principles-based simulations. This could potentially speed the time and reduce the cost to development of a new material, as well as helping to identify promising new materials.

Improved semiconductor detector device fabrication is being pursued in numerous R&D activities at the national laboratories, universities, and industry. An aggressive effort is being applied at these institutions to further the development of electronic devices necessary to perform the readout and computational responsibilities on sensor systems. Requiring smaller radiation detection systems (like handheld devices) with ever-increasing performance as an RIID places high demands on the supporting electronics performance. Faster, lower-power micro-processors are required to handle the required compute capacity for high-performing ID algorithms and larger data sets. The desire for processing algorithm flexibility and adaptation of enhancements is driving small sensor platforms to incorporate field-programmable gate array (FPGA) technology. As well, lower power, higher dynamic range, less noisy, and faster ASICs are being developed to meet the increasingly challenging pulse processing needs of these detectors.

Incremental improvements in photomultiplier tubes (PMTs) used as readout devices for scintillator detectors have been made by various companies, including extending the useful range of wavelengths to which the PMT is sensitive. In addition, new photon detectors that may rival the workhorse PMT are being developed, from avalanche photodiodes (APD), to hybrid photodiodes (HPD), to silicon photomultiplier tubes (SiPMTs), and others. Hybrid photodiodes are silicon-based devices, which have much higher resolution for single and multiple photoelectrons than do ordinary PMTs. This can, in turn, enhance the ease of calibration and the stability of detector response. For some scintillators, notably CsI, the longer wavelength of emitted light allows higher quantum efficiency (related to the effectiveness of light to charge conversion) silicon device readouts can be used. As an example, exceptional resolution has been demonstrated when CsI(Tl) is used with a mercuric iodide photocell in place of a PMT. With this combination, resolution at 662 KeV of better than 5% has been reported, compared to 8% in a typical PMT-read CsI detector.

Quantum efficiency, a key figure of merit for photosensors, has hovered at about 20–25% for many years (in the visible wavelength region of interest for most scintillators). Recent efforts have been made to overcome this apparent barrier to resolution, both in ordinary PMTs, and through the use of APDs and other devices. APDs, for example, offer much higher quantum efficiencies than PMTs, however, at the cost of smaller device active areas, and also suffer from an inability to resolve single photoelectrons. Additional R&D is required in this area to overcome these deficiencies.

Gamma-Ray Spectroscopy Shortfalls

Although medium-resolution (1–3%) semiconductor and scintillator devices are now appearing on the market, the unit costs are relatively high, availability is low, and the physical size of devices is too small for many nonproliferation applications. Adopting the example of CZT, perhaps the most successful medium-resolution semiconductor detector currently under development, the yield of spectroscopic quality single crystals from a growth run is still rather poor. This tends to drive costs high despite many years of development effort in industry, academia, and government labs. CZT resolution might very soon be brought to the sub-percent level with advanced readout techniques and/or improved materials performance. For the otherwise attractive lanthanum bromide/chloride class of scintillator detectors, the intrinsic radioactive background due to ^{138}La may be a significant problem for the relatively large-volume (tens of cubic centimeters) detectors of interest for nonproliferation applications.

As mentioned above, there is a mismatch between the typical emitted wavelength from common scintillators, and the optimal wavelength for photosensing in readout devices such as PMTs. The earlier discussed example of coupling CsI to silicon shows the potential benefit from a better match in the collection and emission wavelengths. Further research is needed into the possibility of extending the emission spectrum of scintillators to longer wavelengths, or improving quantum efficiencies of readout devices in the 300–450 nm (visible) range.

Gamma-Ray Imaging and Directional Detection Overview

Gamma-ray imaging and directional systems identify and display spatial information about one or multiple sources of radiation in a senor defined field of view. There are several methods available to radiation imaging: proximity localization, mechanical collimation, temporal collimation, and electronic collimation. The performance trade-offs in all of these approaches is between image creation efficiency, image resolution (which is dictated by both the intrinsic energy and angular resolution of the system), and fieldability concerns.

Proximity Localizing Detectors

Counting or spectroscopic sensors can be used to build up radiation field images based on the varying amount of radiation reaching a detector or array of detectors in a given time period, due to the changing detector response as a function of the relative position of the detector with respect to the radiation source. As an illustration, count rates can be measured by a single detector at multiple locations at a site of interest containing one or more radiation sources. Source localization is determined by mapping (in 1D, 2D, or 3D) the changes in count rate as a function of detector location. Alternatively, an array of detectors can function as proximity sensors to generate an overall multi-dimensional pattern of the radiation field. Sensors and sources may be fixed or in motion, on vehicles or carried by personnel. In some concepts of operation, additional benefit can be realized by making the detectors location aware (for example using GPS localization) and automatically transmitting individual sensor information to a central location in order to build a radiation field image.

Mechanically Collimating Detectors

Mechanically collimating imagers use passive shielding such as lead or tungsten, or active (gamma-sensitive) collimators between the radiation source and detector to deduce the location of sources. The classical example is the pinhole imager where light or gamma rays are required to pass through a small aperture before entering into the photosensitive media (much like an ordinary visible light camera). Pinhole collimating devices can produce high spatial resolution images, but at the cost of low efficiency since most of the radiation incident on the camera is rejected. Coded-aperture systems are a more sophisticated type of spatially collimating device, in which a specially designed mask is used to encode a pattern on a backing array of detectors. The pattern is then decoded to map the incident gamma-ray flux, in one or two dimensions. Coded-aperture systems can have detection efficiencies approaching 50%, yet suffer from relatively limited field of view, and in some cases degradation of performance in complex or high-level radiation fields. In general, collimators can add significant physical size and weight to any gamma-ray imaging system, an important consideration for fieldable devices. Mechanically collimating imagers perform best at low and medium gamma-ray energies, and for very low-energy neutrons as well. At higher energies, the radiation particles can penetrate the collimator materials, reducing the effectiveness of the mask. There are many gamma-ray sources of interest, including SNM and radiological threats, which exhibit gamma-ray energies within the sensitivity range of these systems.

Temporally Collimating Detectors

Temporally collimated detectors employ time varying masks interposed between a detector and source to encode a pattern in the detector, which depends on the source location. A pair of rotating grids in front of a scintillator detector is an example of such a system. These systems can achieve high angular resolution, and have the advantage that the backing detector can be simple and low energy resolution, and in particular need not be pixilated, since the encoding of the image is taking place in the time domain. As with mechanical collimators, the collimator weight is an important consideration, and the shield/mask may in principle itself be a gamma-sensitive device, i.e., a detector. Unique to this class of device is that they suffer from the relatively heavy modulating collimator being in local motion relative to the detector on ~Hz time scales, which makes large portable devices difficult to achieve. This concern can perhaps be somewhat mitigated by the use of active collimators.

Electronically Collimating Detectors

Imaging is also achievable by recording multiple interactions from the same gamma-ray in a detector or an array of detectors. With the appropriate knowledge of positions and energy loss of two or more interactions, a 2D or 3D image of the incident radiation field can be reconstructed. Compton cameras, in which at least two successive interactions from the same incident gamma-ray are recorded, are the most prominent example of this genre. The absence of a collimator aids with fieldability, but additional expense comes from the fact that the detectors must often be more sophisticated in order to track, record, and process multiple interactions, putting a premium on acquisition speed and on-board computing capability. Whereas it was discussed that mechanically collimated imagers are more effective for low-energy gammas, electronically collimated detectors tend to favor higher-energy operation where Compton interactions are more likely than photoabsorption.

Hybrid Spectroscopic Imaging Systems

Imagers can exploit both coded-aperture and Compton reconstruction approaches simultaneously, to span the full energy range of interest in national security applications. Furthermore, any of the imaging approaches just described can be performed with spectroscopic detectors to aid in isotope identification capability and to create isotope specific radiation intensity maps.

Table A1 summarizes the anticipated operational parameter ranges for the most common gamma-ray imaging methods. These parameters are derived both from theoretical considerations and from practical experience with real devices. Trade-offs among parameters can be partially assessed with the help of this table. For example, the most advanced Compton cameras can have high energy and angular resolution, but will probably have higher per unit costs compared to other imaging systems. The actual R&D effort to approach these achievable limits varies from case to case, and is discussed in the roadmap section of this document.

Table A1. Representative parameters for five main types of gamma-ray imaging methods.

Parameters	Proximity	Collimator	Coded Aperture	Time Modulating	Compton Camera
Imaging Dimensions	1 or 2	1 or 2	2 or 3	2 or 3	2 or 3
Field of View [deg]	30–360	< 60	< 60	< 60– 360	180 or 360
Angular Resolution [deg]	> 30	< 30	< 5	< 1 or > 10 depending on type	1 to 5
Energy Resolution[T1]	Very poor–excellent				
Imaging Efficiency	Poor	Very poor	Good	Good	Good
Contrast	Poor	Excellent	Good	Good-very good	Very good
Minimum Weight (kg)[T2]	0.1	20	20	20	0.5
Weight-Ratio[T3]	10–90%	<< 10%	< 10%	< 10%	> 50%
Achievable Scale[T4]	Large	Medium–Large	Large	Small	Medium–large
Cost	Low	Low	Low–medium	Low–medium	Medium–high

T1. The energy resolution depends on the type of used detector. For instance, a rotation modulation system can be built with a high-resolution HPGe or low-resolution NaI(Tl) detector.

T2. Minimum weight is energy dependent. To have reasonable efficiency at high energy requires more material. Numbers given in table correspond to detectors relevant for ~500 MeV gamma-ray energies.

T3. The weight ratio reflects the weight of the sensitive detector volume to the total weight of the instrument. For collimator-based systems, the total weight is dominated by the collimator and potentially required shields. For room-temperature operated Compton imagers the weight ratio can be increased to > 70%. Cryogenically cooled systems require cooling with associated increase in weight and power. The exact ratio will depend on the platform and other potential constraint. The numbers quoted here reflect potentially achievable ratios.

T4. Large scale in this context is defined as square meter surface area, small scale is 0.1 meter typical linear dimension.

Current Examples of Gamma-Ray Imaging Detectors

Many imaging systems have been built and used in a wide variety of applications, particularly in the medical field. However, imaging detectors available today are with a few exceptions not designed for nonproliferation needs. This points to an obvious R&D gap, which is now beginning to be addressed by NA-22 and other agencies. Examples of currently available imaging or directionally sensitive gamma detectors include:

- *Coded-aperture imagers*—imagers that utilize a mechanical mask to encode the directions of incident gamma rays on position sensitive gamma-ray detectors. Deconvolution of the raw signal is required.
- *Compton cameras*—imagers that rely on the kinematics of Compton scattering to determine the incident angle of the gamma ray. Raw data must be processed to reveal image.
- *Modulating collimators/Fourier transform systems*—imagers that utilize temporally varying signal, either induced by moving aperture or moving imager. Image processing is required.

Current R&D for Gamma-Ray Imaging and Directionality

Current R&D efforts underway include the following:

- **Exploration of parameter space versus nonproliferation-related concepts of operations.** At least one study is underway into the important question of how particular gamma-ray imaging methods map to particular end user needs in the nonproliferation community. Partial results from this study are shown in Table A1. A detailed mapping of user needs to individual technologies is now in preparation, but some general trends are clear. For example, true handheld systems are likely to be based on proximity imaging or possibly Compton imaging, due to the substantial reduction in system weight associated with these collimator-free approaches. All of the collimated systems may potentially be useful in truck mounted or fixed applications.
- **Distributed systems and proximity imaging.** Several national lab efforts are focused on developing medium to large arrays of hand-held detectors, which can be used collectively to perform wide-area proximity imaging. Efforts are focused on low-cost production of large quantities of detectors, and on synthesizing the array data into a useful image, possibly in real time.
- **Coded-aperture systems.** NA-22 and DHS' Domestic Nuclear Detection Office (DNDO) have funded work on improving the fieldability and commercializing a coded-aperture system.
- **Time-modulating collimators.** Considerable effort has been devoted by NASA into development of temporally modulated imagers for astrophysical research, including RHESSI (Reuven Ramaty High-Energy Solar

Spectroscopic Imager),* and Hinotori, respectively, U.S. and Japanese satellite-borne experiments. Rotating modulating collimators and related ideas have only recently been proposed for nonproliferation applications.

- **Compton cameras.** Several efforts within NA-22 and DNDO are underway to develop portable, robust, more-efficient, and higher-resolution Compton imaging systems. As with time-modulating collimators, many years of R&D have been invested in development of space-based Compton imagers. This R&D can be and has been adapted where relevant for nonproliferation applications.

Gamma-Ray Imaging and Directionality Shortfalls

The gaps in gamma-ray imaging research are many. For systems that depend on multiple separate pixel detectors, including coded-aperture imagers and some types of Compton imagers, the imaging performance is limited at the level of the pixel by essentially the same shortfalls encountered in gamma spectroscopy; material expense and availability, crystal growth problems, and limitations on readout imposed by available electronics. This translates into a variety of shortcomings for imaging performance, including degraded position resolution relative to the theoretical maximum, and low efficiency for creating an image. Improved methods of inter-calibration between pixels in these multipixel devices are also needed.

High pressure (10–20 atmospheres) noble gas TPCs have been considered in the past for gamma-ray imaging, but interest has wavered for some of the same reasons now being addressed in the context of neutron imaging: microphonics, heavy pressure vessels, and a complicated readout mechanism. In addition, the requirement of a heavy pressure vessel not only represents a mobility and accessibility impediment, but also renders the approach somewhat ineffective in examining lower-energy gamma rays. There is currently only a minimal amount of ongoing research in this area. Recent advances in TPCs for basic physics research has demonstrated some performance improvements in reducing microphonics noise, making available lighter pressure vessel materials, and improving readout electronics in recent years.

More work is also needed in optimizing image reconstruction algorithms specifically for nonproliferation applications, whose requirements differ from the medical and astrophysical fields where most imaging algorithms have a long history of development.

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* G.J. Hurford, E.J. Schmahl, R.A. Schwartz, A.J. Conway, M.J. Aschwanden, A. Csillaghy et al., "The Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI)," *Solar Physics,* Vol. 210, pp. 61–86, 2002.

Overview of Photon Sources

There are a number of commercially available (VACIS, CX-9000F) and developmental systems (CAARS) for SNM detection based on photon interrogation. While each of these systems may exploit different signatures, they each rely on a source of x rays or gamma rays to stimulate the item under inspection. Because of the widespread utilization of x-ray sources in the medical community, techniques for producing photons and the associated technology is comparatively inexpensive and well understood. Utilization of photon sources for SNM detection, however, requires novel sources that are appropriately tailored for the specific task of active interrogation. To date, photon sources such as linear accelerators (linacs) have been taken from the medical community and customized to conduct a specific task. In some cases, these sources may not be ideal for deployment in inspection scenarios. Historically, photon sources have been divided between isotopic sources and accelerator generated sources. Since isotopic sources of gamma rays are limited to energies below 2.8 MeV, they have been utilized almost exclusively in imaging systems that can provide better penetration than lower-energy x-ray systems.

For the accelerator-driven photon sources, linacs are currently the device of choice for the production of photons with energies in the range of 2–30 MeV. Photons produced in this range are generated by bombarding high-energy electrons into conversion targets thereby generating a bremsstrahlung source having a broad spectrum of energies. Since the production of bremsstrahlung is a function of Z^2, high-Z targets such as tungsten are often used. To a much lesser extent, sources that utilize synchrotron losses from high-energy electrons or gamma rays produced through nuclear reactions have been explored as photon sources.

Current Examples of Photon Sources

Isotopic Sources

As the name suggests, isotopic sources produce gamma rays through the decay of unstable isotopes. Compared to accelerator-driven sources, they have the advantage that they do not need a supply of electrical power to function, but they do have the disadvantage that they cannot be turned off. Due to the isotropic distribution of the decay gammas, it is difficult to create a compact source that generates a comparable photon flux available from electrically driven sources.

Isotopes are available that provide a wide range of available gamma-ray emission with energies in the range of tens of keV up to about 2.8 MeV. Two of the most commonly used isotopic sources, ^{60}Co and ^{137}Cs, produce only a few gamma energies which make them essentially monochromatic. These sources have been widely used in imaging systems since their gamma rays are much more penetrating than those from conventional x-ray tubes. Other isotopes such as ^{192}Ir and ^{57}Co emit gamma rays with lower photon energies than ^{60}Co and ^{137}Cs, which may be advantageous for imaging since these lower energies can give provide improved contrast. Isotopic sources are generally too low in energy for utilization in photonuclear inspection scenarios. To achieve energies above 3 MeV, accelerator-based sources are required.

Accelerator-produced Photon Sources

Accelerator-driven sources are by far the most common, currently available means to produce large fluences of high-energy photons. When energetic electrons interact in material, a portion of their energy is converted into electromagnetic radiation in the form of bremsstrahlung photons. The fraction of energy converted into photons increases with electron energy and has a dependence that is proportional to Z^2 of the converter material. This type of photon source provides a forward-directed continuous energy spectrum that extends to the maximum energy of the electron. The electron linac consists of an injector, a linear accelerating structure, a supply system for accelerating structure, a converter for the production of photons and associated vacuum and control systems. A related, although less frequently utilized, type of photon source employs an oscillating magnetic field to bend a high-energy electron beam.

Synchrotron radiation is emitted when charged particles, usually electrons or positrons, moving at relativistic speeds, are forced to change direction under the action of a magnetic field. The electromagnetic radiation is emitted in a narrow cone in the forward direction, at a tangent to the particle's orbit. Synchrotron light is unique in its intensity and brilliance and it can be generated across the range of the electromagnetic spectrum: from infrared to x rays.

Current R&D for Photon Sources

Monoenergetic Photons

When broad-spectrum bremsstrahlung sources are used to interrogate for SNM, a large fraction of the photons produced do not have sufficient energy to stimulate either a (γ,n) , (γ,fission) or (γ, γ') reaction, which can be used to identify materials of interest. For photonuclear processes (with a few NRF exceptions), gammas below ~5 MeV will not contribute to useful signals and will contribute only to unwanted dose. Additionally, it would be advantageous in various applications to have the ability to tune the energy of the incoming photon to match the maximum cross-section for various reactions in the giant dipole region (13–16 MeV). For applications utilizing NRF, a tunable gamma-ray source in the energy range of 0–8 MeV would be necessary. A number of current research projects are investigating ways to produce tunable high-energy photons with sufficient fluences for use in SNM inspection.

- Laser/Electron Interactions

The head-on scattering of relativistic electrons (> 200 MeV) and laser photons produces a forward scattered beam of nearly monoenergetic photons. The energy of the up-scattered photon is related to the electron energy and laser energy by the following equation:

$$h\nu_{scatter} = 4\gamma^2 h\nu_{laser}$$

Examples of this type of source are being investigated trough the T-REX project at Lawrence Livermore National Laboratory and the HIγS project at Duke.

- Nuclear Reactions

When protons or deuterons of sufficient energy interact with low-*Z* materials, nuclear reactions can be induced, which result in a series of monoenergetic gamma-rays. In order for the photon to be usable for SNM detection, the photon energy must be high enough to produce large photofission signals, while minimizing photoneutron production in common cargo materials which can interfere with the signatures from HEU or plutonium. The most promising proton-induced reactions being studied are the nuclear resonances at 163 keV for the $^{11}B(p,\gamma)^{12}C$ reaction producing 11.7 MeV gamma rays, 340 keV for the $^{19}F(p,\alpha\gamma)^{16}O$ reaction producing 6.13 MeV photons, and 441 keV for the $^{7}Li(p,\gamma)^{8}Be$ reaction producing 14.8 and 17.7 MeV photons.

Bremsstrahlung Converter/Collimator Optimization

The majority of technologies utilizing bremsstrahlung photon sources for SNM interrogation are negatively affected by the presence of excess background neutrons from the converter. If the photon energy produced is above the neutron separation threshold (6–8 MeV for most materials), neutrons will be produced in the converter/collimator region of an electron linac. In order to tailor the photon spectrum for a specific application, the optimization of the converter/collimator combination must include: maximizing the forward peaking of the radiation, minimization of extraneous neutrons, and maximization of the photon flux.

Laser Wakefield Acceleration

Typical linear electron accelerators are limited to accelerating gradients of < 10–20 MV/m. Laser wakefield acceleration can achieve gradients in excess of 30 GeV/m, which could result in extremely small high-energy accelerators. Wakefield acceleration is accomplished by introducing waves of very high charge separation that travel through plasma. Such a wave can be created by applying a high-power laser into properly prepared plasma. As this pulse travels through the plasma, electrons and nucleons are separated by the electric field of the light photon. Due to the large mass difference between the electron and the nucleon, the electrons move much faster than the nucleons, resulting in an area of charge separation. These electrons are pulled back towards the area of positive charge as the light photon vacates the region of the charge separation. As the electrons accelerate into this area of positive charge, they pile up briefly before losing this energy in collisions. This leads to a small area of very strong potential gradient following the laser pulse. It is this “wakefield” that is used for particle acceleration.

Appendix A: Technology Overview

Shortfalls of Photon Sources

There are a number of shortfalls in existing photon sources that limit their applicability for field application in the detection of SNM. As noted previously, bremsstrahlung-based sources produce a broad spectrum of photon energies that may not be useful for inspection. Photons that are below the useful energy contribute to background signal, which may interfere with measurements and result in unwanted dose. This concern over the dose both to the general public and the operator of the interrogation system as well as the item under inspection is an area of research which must be addressed for current and future systems. In nearly all conceivable applications of photon sources there is a possibility for exposing humans. As a result, these sources will likely be subject to some form of radiation dose limits. The National Council for Radiation Protection (NCRP) has established a limit for one time dose equivalents of 100 mrem for normal screening, and for purposes of national security the suggested limit is increased to 500 mrem. For most applications utilizing bremsstrahlung sources, the necessary dose for an inspection of 1–2 minutes will be near these limits. Clearly, any unwanted dose that does not contribute to useful signal is a detriment.

Monoenergetic sources—which may, in fact, reduce the needed dose on target for a successful inspection—suffer from a different problem. In the case of charged-particle induced reactions, the emitted gamma-rays are isotropic. This requires that huge amounts of beam power be placed on target to achieve a reasonable photon flux. Similarly, laser scattering sources require large electron accelerators and powerful lasers to achieve sufficient photon fluences. More work is required to reduce the size and required power of these novel monoenergetic photon sources to the point where they become feasible and economically viable for deployment.

Overview of Neutron Sources

Neutron sources have historically been developed for a variety of applications and can produce neutrons in wide ranges of energy from a few hundred keV up to 14 MeV. Well-known neutron generators employing the D-D or D-T reaction comprise small, sometimes portable accelerators that project beams of deuterons onto deuterated or tritiated targets. These sources emit neutrons nearly isotropically as a consequence of the reaction Q-value (e.g., energy liberated in the reaction of the D-D and D-T reaction is much larger than the accelerated deuteron energy). These are endoergic reactions and can proceed once the Coulomb barrier for the reactants is overcome. Larger particle accelerators such as single-ended or tandem Van de Graff's or Radio Frequency Quadrupole (RFQ) have also been used to generate neutrons. These machines can accelerate protons or deuterons up to energies of a few MeV and then impinge the charged particles onto low-Z targets such as lithium or beryllium to produce large amounts of neutrons. Isotopic sources of neutrons in the form of ^{252}Cf, or (α,n) sources based on combination of alpha-emitters (like Po and Pu) with beryllium or lithium are readily available.

Current Examples of Neutron Sources

Most neutron sources today are either accelerator based that rely on D-D or D-T reactions or are radioactive source based, such as ^{252}Cf or Pu-Be based on (α,n) reactions. All of these types of sources are commercially available in some form today, although they may not meet the challenging field requirements or neutron output desired for SNM active interrogation applications.

Current R&D for Neutron Sources

There is a wide array of current R&D efforts being pursued to further develop these sources, or to develop completely new classes of neutrons sources exhibiting favorable fieldability and/or performance characteristics relevant to SNM interrogation. Some highlights are as follows:

- **Field desorption.** Neutron-generator sources based on electrostatic field desorption are currently being investigated. This work has the potential of using standard integrated-circuit manufacturing techniques to produce very efficient, low-power, long-lifetime deuterium-ion sources for neutron generation readily scalable in the expected range from 10^7 to 10^{12} n/sec, enabling a very light-weight (~20 pound) portable neutron source for active interrogation. At its core, this technique relies on electric field concentration at micron-sized metal tips to field liberate absorbed deuterium gas (D_2) from the surface in the form of singly charged deuterium ions (D^+).
- **Compact tube-based neutron sources.** RFQ-generated plasma ion sources have been designed to drive relatively small, tube-like reaction based neutron source cavities. This technique has demonstrated neutron output up to 10^{10} n/sec at 2.5 MeV exploiting the D-D reaction. A new design which could improve performance to 10^{12} n/sec is currently being pursued. An approach for a higher-voltage tube is being pursued, which could use the ^{7}Li(d,n) reaction to produce 13.5 MeV neutrons without requiring the use of tritium. As discussed above in the gamma source section, this approach is also being actively pursued for producing a compact, single or several energy gamma sources.
- **Kinematically collimated neutron source.** The kinematically collimated low-energy neutron concept takes advantage of the ^{7}Li(p,n) reaction which has an energy threshold of 1.88 MeV. By bombarding a lithium target with protons (which are approximately 100 keV above the neutron production threshold), low-energy neutrons that are kinematically collimated (forward directed by virtue of reaction kinematics) are produced. Nearly all neutrons produced are forward directed within a 60º cone. These neutrons are then directed toward the material of interest (cargo container, package, etc.). If fissile material is present, fissions will occur that produce neutrons, which have energies far greater than 60–100 keV. By utilizing liquid scintillators and pulse-shape discrimination, the radiation emitted during an inspection

can be monitored for more energetic neutrons (typically greater than about 500 keV), indicating the presence of fissile material. Detection of the higher-energy neutrons can be accomplished during or shortly (few microseconds) after an interrogating pulse.

Shortfalls of Neutron Sources

Currently available neutrons sources suffer significant shortfalls in that they are generally of too low in neutron intensity to be effective for detection, identification, or characterization in reasonable interrogation time, shielding, and standoff constraints. The also for the most part tend to be isotropic, so that neutron emission is roughly equally distributed in all spatial directions. The consequence is that significant shielding, remote operation, or significant radiation does to operators or others in the vicinity could result. In the case where radioactive source-based neutron generators are employed, significant shielding is often required. This can significantly reduce the fieldability of such a source. In the case of accelerator based systems, source lifetime and fragility are also major issues.

Overview of Other Sources

Sources of interrogating radiation other than photons and neutrons may be of interest in SNM detection, particularly as unique induced signatures of SNM are discovered and as greater standoff detection is desired. There is a consistent push for standoff capabilities at ever increasing distances from a suspected threat target. Non-photon or neutron-based techniques could offer additional capability not available to more conventional sources. To that end, two exotic methodologies are being explored that show potential of being operable at long-range detection at distances of several hundred meters to, perhaps, a few kilometers.

Current Examples of Other Sources

There are many examples of non-photon/neutron high-energy particle sources that produce output in energy ranges of interest to SNM detection. These, however, tend to be very-large-scale, high-energy physics tools that are only well suited for laboratory investigation. The substantial R&D challenge will be to make these technologies available to portable, transportable, re-locatable, or even simply fixed field installation sources that have particle output performance properties appropriate for interrogation of SNM. In most cases this implies significant increases in source intensity, sometimes several orders of magnitude beyond what is currently achievable, while at the same time significantly reducing the footprint and power requirements.

Current R&D for Other Sources

Two such examples currently being considered for use in SNM detection schemes include high-energy (> 1 GeV) protons and negative muons (600–800 MeV).

- **High-energy protons.** Protons greater than 1 GeV can be transported distances of a few kilometers in air without appreciable attenuation or scattering of the beam to an unacceptable intensity. These charged particles would be produced by a large particle accelerator housed on a ship or large military aircraft and directed at items of interest at standoff distances of >1 km. Protons at these energies generate a large shower of charged and uncharged particles, which propagate through the item being inspected. Because of the wide range of particles and energies produced, there are a number of reactions occurring, which either directly or indirectly lead to fission if SNM is present. In order to detect the SNM, delayed neutrons and gammas would be monitored between accelerator pulses.
- **High-energy muons.** High-energy negative muons can be produced via interactions of high-energy electrons with appropriate target materials. Some of the muons would be captured and injected into a further acceleration stage to provide the required beam properties for high-energy negative muons. Since they are charged particles, these muons propagate through solid materials and gradually lose energy. Eventually, when slowed substantially, the negative muons would be captured in SNM atomic orbitals and emit characteristic x rays as it cascades down the atomic structure. Owing to the large mass of the muon and the large nuclear charge of HEU and plutonium, the x rays generated in this process for low-lying transitions have energies in the MeV range. As with all characteristic emission, these x rays are unique signatures of individual elements, and in this case, individual isotopes, allowing for the potential of unique identification of threat materials.

Shortfalls of Other Sources

The significant shortfalls in these approaches are size, complexity, power consumption, and fragility of many accelerators for non-photon/neutron sources. All areas are ripe for investigation into novel approaches that may yield fieldable systems utilizing these more exotic sources of interrogation radiation. This is an extremely high risk and far-off solution that will require substantial long term investment and a number of enabling technology leaps before the community can begin to envision a practical application.

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Appendix B: Data for Requirement 1—Detect Shielded HEU

Appendix B: Data for Requirement 1—Detect Shielded HEU

The data in the **Table B1** was collected in the roadmap process for the identification of technologies to address Requirement 1 (Shielded HEU Detection). These data are organized by ConOp, Technical Area, and Technical Class. The data include Shortfalls or characteristics desired of passive detection systems. Items that appear in bold type are deemed to be the most important feature. The additional shortfalls or characteristics imposed by active interrogation are included in a separate column. The maturity of the technology uses the DoD 6.0–6.3 rankings. Technical risk is ranked high = 1, medium = 2, and low = 3. Impact is ranked high = 1, medium = 2, and low = 3. (Maturity, risk, and impact are defined in the Technology Assessment by Requirement section.) Estimated target funding per year is given in millions of dollars, and the time required for development to demonstration is provided in years. The enabling technology requirements column provides the working groups assessment of the additional needs for enabling technology R&D to support the more complete development required in that technology class to meet the requirements of the mission program.

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp.

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics— Passive	Shortfalls/ Characteristics— Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Search	Large-area detectors—thermal	Large area (1 m^2), **high efficiency**, background discrimination, low **weight**, conformal, high gamma discrimination; transportable ^{3}He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.2	2	3	1	3	
Neutron Correlation	Search	Large-area detectors—high energy	Large area (1 m^2), **high efficiency**, background discrimination, **low weight**, conformal, high gamma discrimination; transportable ^{3}He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	1	2	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Search	Solid-state neutron detectors	Deployable system design, **must be person portable**, 100 cm^2 detector volume or larger, **high efficiency**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	1	3	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Search	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Real-time readout, recovery	6.1	2	2	1	3	

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Search	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Correlation	Contain/Screen	Solid-state neutron detectors	**Direct detection of high-energy neutrons**, deployable, mobile, large area (1 m^2), high **efficiency, good** gamma discrimination	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	1	3	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Contain/Screen	Large-area detectors—thermal	Large area (1 m^2), **high efficiency**, background discrimination, low **weight**, conformal, high gamma discrimination; transportable ^3He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.2	2	2	1	3	
Neutron Correlation	Contain/Screen	Large-area detectors—high energy	Large area (1 m^2), **high efficiency**, background discrimination, **low weight**, conformal, high gamma discrimination; transportable ^3He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	1	2	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Contain/Screen	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Real-time readout, recovery	6.1	2	3	1	3	
Neutron Correlation	Contain/Screen	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Correlation	Characterize	Solid-state Neutron detectors	**Direct detection of high-energy neutrons**, deployable, mobile, large area (1 m^2), high **efficiency, good** gamma discrimination	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	3	3	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Characterize	Large-area detectors—thermal	Large area (1 m^2), **high efficiency**, background discrimination, low **weight**, conformal, high gamma discrimination; transportable ^3He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.2	2	3	1	3	

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Characterize	Large-area detectors—high energy	Large area (1 m^2), **high efficiency**, background discrimination, **low weight**, conformal, high gamma discrimination; transportable ^{3}He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	2	2	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Characterize	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Real-time readout, recovery	6.1	2	3	1	3	
Neutron Correlation	Characterize	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Spectroscopy	Search	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Spectroscopy	Contain/Screen	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Spectroscopy	Characterize	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	2	3	9	
Neutron Spectroscopy	Characterize	Ultra-high resolution neutron spectrometry	Must reduce size, need high efficiency, ability to tolerate high rates, increased deployability, **rapid sample change capability**	NA	6.2	3	3	1	6	

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics— Passive	Shortfalls/ Characteristics— Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Imaging	Search	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Imaging	Search	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.2	2	3	1	3	
Neutron Imaging	Contain/Screen	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Imaging	Contain/ Screen	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.2	2	3	1	3	
Neutron Imaging	Characterize	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	2	3	9	
Neutron Imaging	Characterize	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.2	2	2	1	3	
Gamma Correlation	Search	Gamma detection—timing, multiplicity, signatures	Timing capability from ns–μs, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	1	3	6	Afterglow may be a materials issue, PSD, high-*Z* loading…

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics— Passive	Shortfalls/ Characteristics— Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Gamma Correlation	Contain/Screen	Gamma detection—timing, multiplicity, signatures	Timing capability from ns to us, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	1	3	6	Afterglow may be a materials issue, PSD, high-Z loading...
Gamma Correlation	Characterize	Gamma detection—timing, multiplicity, signatures	Timing capability from ns to us, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	1	3	6	Afterglow may be a materials issue, PSD, high-Z loading...
Gamma Spectroscopy	Search	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	2	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT
Gamma Spectroscopy	Search	Algorithms for ID in active systems		Time sequence analysis of spectra, Identification of short lived fission and activation products	6.1	1	3	2	6	Measure decay scheme data S&O
Gamma Spectroscopy	Contain/Screen	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detector	6.1	1	3	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT
Gamma Spectroscopy	Contain/ Screen	Algorithms for ID in active systems		Time sequence analysis of spectra, Identification of short lived fission and activation products	6.1	1	3	2	6	Measure decay scheme data S&O

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Gamma Spectroscopy	Characterize	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT, NRF signatures
Gamma Spectroscopy	Characterize	Algorithms for ID in active systems		Time sequence analysis of spectra, identification of short lived fission and activation products	6.1	1	2	2	6	Measure decay scheme data S&O
Gamma Imaging	Search	Mechanically collimated systems	Advance designs for high energy resolution and **dynamic range**, improve image quality	Source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow materials	6.2	2	3	1	3	
Gamma Imaging	Search	Electronically collimated system	**Large active volume**, high efficiency, medium to high energy resolutions, reduced complexity, reduce cost, **field deployment capable, ease of use**	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	3	10	6	ASIC development, gamma spectroscopy materials
Gamma Imaging	Contain/Screen	Mechanically collimated systems	Advance designs for high energy resolution and **dynamic range**, improve image quality	Source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow materials	6.2	2	3	1	3	
Gamma Imaging	Contain/Screen	Electronically collimated system	Large active volume, **high efficiency**, medium to high energy resolutions, reduced complexity, reduce cost	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	3	10	6	ASIC development, gamma spectroscopy materials
Gamma Imaging	Characterize	Mechanically collimated systems	Advance designs for high energy resolution and **dynamic range**, improve image quality	Source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow materials	6.2	2	2	1	3	

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Gamma Imaging	Characterize	Electronically collimated system	Large active volume, **high efficiency**, medium to high energy resolutions, reduced complexity	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	2	10	6	ASIC development, gamma spectros-copy materials
Photon Source	Search	Broad spectrum		Good collimation, high end-point energy, high flux, pulsed for (photo fission), DC for NRF, selectable energy end point, **light weight**, low energy consumption, **reduced dose to user,** beam hardened**,** beam manipulation capability	6.2	3	1	8	6	Driven by industry
Photon Source	Search	Monoenergetic		**Forward directed**, good collimation, high energy, **high flux**, pulsed (photo fission), DC for NRF, **tunable energy (LCS), select-able energy (reaction based sources)**, light weight, low energy consumption, reduced dose to user, beam manipulation, power supply size	6.1	1	1	20	9	Compact high power laser
Photon Source	Contain/Screen	Broad spectrum		**Good collimation**, high end-point energy, high flux, pulsed for (photo fission), DC for NRF**,** selectable energy end point, light weight, low energy consumption, **reduced dose to use**r**,** beam hardened**,** beam manipulation capability	6.2	3	1	8	6	Driven by industry

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Photon Source	Contain/Screen	Monoenergetic		**Forward directed**, good collimation, high energy, **high flux**, pulsed (photo fission), DC (NRF), **tunable energy (LCS), selectable energy (reaction-based sources)**, light weight, low energy consumption, reduced dose to user, beam manipulation, power supply size	6.1	1	1	20	9	Compact high power laser
Photon Source	Characterize	Broad spectrum		**Good collimation**, high end-point energy, high flux, pulsed for (photo fission), **DC for NRF,** selectable energy end point, light weight, low energy consumption, reduced dose to user**, beam hardened,** beam manipulation capability	6.2	3	1	8	6	Driven by industry
Photon Source	Characterize	Monoenergetic		**Forward directed**, good collimation, high energy, **high flux**, pulsed (photo fission), DC (NRF), **tunable energy (LCS), selectable energy (reaction-based sources)**, light weight, low energy consumption, reduced dose to user, beam manipulation, power supply size	6.1	1	1	20	9	Compact high power laser
Neutron Source	Search	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchronization, **reduced dose to user,** improved ion source, power supply size	6.1	2	1	8	6	Power supplies size

Table B1. Requirement 1—Detect shielded HEU R&D technology development data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Source	Search	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	2	1	5	3	
Neutron Source	Contain/Screen	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchroniza-tion, **reduced dose to user,** improved ion source, power supply size	6.1	2	1	8	6	Power supplies size
Neutron Source	Contain/Screen	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	3	1	5	3	
Neutron Source	Characterize	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchronization, **reduced dose to user,** improved ion source, power supply size	6.1	2	1	8	6	Power supplies size
Neutron Source	Characterize	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	3	1	5	3	
Other Source	Characterize	Muon source, photon source,...		Sources for inter-rogation other than neutron and photons	6.0					Muon x-ray, charged particle, etc. go to S&O for review

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Appendix C: Data for Requirement 2—Detect SNM at Standoff Distances

Appendix C: Data for Requirement 2—Detect SNM at Standoff Distances

The data in the **Table C1** was collected in the roadmap process for the identification of technologies to address Requirement 2 (Standoff SNM Detection). These data are organized by ConOp, Technical Area, and Technical Class. The data include Shortfalls or characteristics desired of passive detection systems. Items that appear in bold type are deemed to be the most important feature. The additional shortfalls or characteristics imposed by active interrogation are included in a separate column. The maturity of the technology uses the DoD 6.0–6.3 rankings. Technical risk is ranked high = 1, medium = 2, and low = 3. Impact is ranked high = 1, medium = 2, and low = 3. (Maturity, risk, and impact are defined in Technology Assessment by Requirement section.) Estimated target funding per year is given in millions of dollars, and the time required for development to demonstration is provided in years. The enabling technology requirements column provides the working groups assessment of the additional needs for enabling technology R&D to support the more complete development required in that technology class to meet the requirements of the mission program.

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp.

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics–Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Search	Large-area detectors—thermal	Large area (1 m^2), high **efficiency**, background discrimination, **platform specific design**, low weight, conformal, high gamma discrimination; transportable ^{3}He tube replacement	Fast gating, high stability, reduce radiation damage	6.1	1	1	2	3	Improved detectors, new detector materials, better light collection/con-version, electronic contacts on semiconductors...
Neutron Correlation	Search	Large-area detectors—high energy	Large area (1 m^2), high **efficiency**, background discrimination, **platform specific design**, low weight, conformal, high gamma discrimination; transportable ^{3}He tube replacement	Fast gating, high stability, reduce radiation damage	6.1	1	1	2	6	Improved detectors, new detector materials, better light collection/con-version, electronic contacts on semiconductors...
Neutron Correlation	Search	Solid-state neutron detectors	Deployable system design, **must be person portable**, 100 cm^2 detec-tor volume or larger, **high efficiency**	Scintillator based approached more suitable for standoff. More appropriate for person portable until further developed	6.1	1	3	3	6	New detectors, systems challenges on readout
Neutron Correlation	Search	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Too low efficiency per unit weight. Real-time readout, recovery	6.1	2	3	1	3	

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics–Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Search	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Correlation	Contain/Screen	Solid-state Neutron detectors	**Direct detection of high-energy neutrons**, deployable, mobile, large area (1 m^2), high **efficiency, good** gamma discrimination	May be applicable for bistatic deployment, priority on low power, gating, speed, stability, radiation damage	6.1	1	3	3	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Contain/Screen	Large-area detectors—thermal	Large area (1 m^2), high **efficiency**, background discrimination, low weight, conformal, **high gamma discrimination**; transportable ^3He tube replacement	Fast gating, high stability, reduce radiation damage	6.2	2	1	2	3	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Contain/Screen	Large-area detectors—high energy	Large area (1 m^2), high **efficiency**, background discrimination, low **weight**, conformal, high **gamma discrimination**; transportable ^3He tube replacement	Fast gating, high stability, reduce radiation damage	6.1	1	1	2	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Contain/ Screen	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Too low efficiency per unit weight, Real-time readout, recovery	6.1	2	3	1	3	
Neutron Correlation	Contain/Screen	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduce radiation damage	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Correlation	Characterize	Solid-state Neutron detectors	**Direct detection of high-energy neutrons**, deployable, mobile, large area (1 m^2), high **efficiency, good** gamma discrimination	Fast gating, high stability, reduce radiation damage	6.1	1	3	3	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Characterize	Large-area detectors—thermal	Large area (1 m^2), **high efficiency**, background discrimination, low **weight**, conformal, high gamma discrimination; transportable ^3He tube replacement	Fast gating, high stability, reduce radiation damage	6.2	2	3	1	3	

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics–Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Characterize	Large-area detectors—high energy	Large area (1 m^2), **high efficiency**, background discrimination, **low weight**, conformal, high gamma discrimination; transportable ^{3}He tube replacement	Fast gating, high stability, reduce radiation damage	6.1	1	2	2	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Characterize	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Real-time readout, recovery	6.1	2	3	1	3	
Neutron Correlation	Characterize	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduce radiation damage	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Spectroscopy	Search	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Spectroscopy	Contain/Screen	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Spectroscopy	Characterize	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Spectroscopy	Characterize	Ultra high-resolution neutron spectrometry	Must reduce size, need high efficiency, ability to tolerate high rates, increased deployability, **rapid sample change capability**	NA	6.2	3	3	1	6	

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics–Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Imaging	Search	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	1	1	3	9	
Neutron Imaging	Search	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.2	2	1	1	3	
Neutron Imaging	Contain/Screen	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	1	1	3	9	
Neutron Imaging	Contain/ Screen	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.2	2	1	1	3	
Neutron Imaging	Characterize	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	1	1	3	9	
Neutron Imaging	Characterize	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.2	2	1	1	3	
Gamma Correlation	Search	Gamma detection—timing, multiplicity, signatures	Timing capability from ns–μs, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	2	3	6	Afterglow may be a materials issue, PSD, high-Z loading...
Gamma Correlation	Contain/Screen	Gamma detection—timing, multiplicity, signatures	Timing capability from ns–μs, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	2	3	6	Afterglow may be a materials issue, PSD, high-Z loading...

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics–Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Gamma Correlation	Characterize	Gamma detection—timing, multiplicity, signatures	Timing capability from ns–μs, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	2	3	6	Afterglow may be a materials issue, PSD, high-Z loading...
Gamma Spectroscopy	Search	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT
Gamma Spectroscopy	Search	Algorithms for ID in active systems		Time sequence analysis of spectra	6.1	1	1	2	6	Measure decay scheme data S&O
Gamma Spectroscopy	Contain/Screen	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT
Gamma Spectroscopy	Contain/ screen	Algorithms for ID in active systems		Time sequence analysis of spectra	6.1	1	1	2	6	Measure decay scheme data S&O
Gamma Spectroscopy	Characterize	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT, NRF signatures

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics–Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Gamma Spectroscopy	Characterize	Algorithms for ID in active systems		Time sequence analysis of spectra	6.1	1	1	2	6	Measure decay scheme data S&O
Gamma Imaging	Search	Mechanically collimated systems	Advance designs for medium to high energy resolution and large dynamic range, better image quality, **high efficiency**	Good source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow	6.2	2	1	1	3	
Gamma Imaging	Search	Electronically collimated system	**Large active volume**, high efficiency, medium to high energy resolutions, reduced complexity, reduce cost, **field deployment capable, ease of use**	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	6	ASIC development, gamma spectroscopy materials
Gamma Imaging	Contain/ Screen	Mechanically collimated systems	Advance designs for medium to high energy resolution and large dynamic range, better image quality, **high efficiency**	Good source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow	6.2	2	1	1	3	
Gamma Imaging	Contain/Screen	Electronically collimated system	Large active volume, **high efficiency**, medium to high energy resolutions, reduced complexity, reduce cost	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	6	ASIC development, gamma spectroscopy materials
Gamma Imaging	Characterize	Mechanically collimated systems	Advance designs for medium to **high energy resolution** and large dynamic range, better image quality, **high efficiency**	Good source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow	6.2	2	1	1	3	
Gamma Imaging	Characterize	Electronically collimated system	Large active volume, **high efficiency**, medium to high energy resolutions, reduced complexity	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	6	ASIC development, gamma spectroscopy materials

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics–Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Photon Source	Search	Broad spectrum		Good collimation, high end-point energy, high flux, pulsed for (photo fission), DC for NRF, selectable energy end point, **light weight**, low energy consumption, **reduced dose to user,** beam hardened**,** beam manipulation capability	6.2	3	1	8	6	Driven by industry
Photon Source	Search	Mono-energetic		Forward directed, good collimation, high energy, high flux, pulsed (photo fission), DC (NRF), tunable energy (LCS), selectable energy (reaction based sources), light weight, low energy consumption, reduced dose to user, beam manipulation	6.1	1	1	20	9	Compact high power laser
Photon Source	Contain/Screen	Broad spectrum		**Good collimation**, high end-point energy, high flux, pulsed for (photo fission), DC for NRF**,** selectable energy end point, light weight, low energy consumption, **reduced dose to user**, beam hardened**,** beam manipulation capability	6.2	3	1	8	6	Driven by industry
Photon Source	Contain/Screen	Mono-energetic		**Forward directed**, good collimation, high energy, **high flux**, pulsed (photo fission), DC (NRF), **tunable energy (LCS), selectable energy (reaction based sources)**, light weight, low energy consumption, reduced dose to user, beam manipulation, power supply size	6.1	1	1	20	9	Compact high power laser

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics– Passive	Shortfalls/ Characteristics— Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Photon Source	Characterize	Broad spectrum		**Good collimation**, high end-point energy, high flux, pulsed for (photo fission), **DC for NRF,** selectable energy end point, light weight, low energy consumption, reduced dose to user**,** **beam hardened,** beam manipulation capability	6.2	3	1	8	6	Driven by industry
Photon Source	Characterize	Mono-energetic		**Forward directed**, good collimation, high energy, **high flux**, pulsed (photo fission), DC (NRF), **tunable energy (LCS), select-able energy (reaction based sources)**, light weight, low energy consumption, reduced dose to user, beam manipulation, power supply size	6.1	1	1	20	9	Compact high power laser
Neutron Source	Search	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchronization, **reduced dose to user,** improved ion source, power supply size, **isotropy issue at distance**, low energy D-D D-T not ideal at distance	6.1	1	1	8	6	Power supplies size
Neutron Source	Search	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	2	3	5	3	

Table C1. Requirement 2—Detect SNM at standoff distances R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics–Passive	Shortfalls/ Characteristics–Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Source	Contain/Screen	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchronization, r**educed dose to user**, improved ion source, power supply size, **isotropy issue at distance**, low energy D-D D-T not ideal at distance	6.1	2	1	8	6	Power supplies size
Neutron Source	Contain/Screen	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	2	3	5	3	
Neutron Source	Characterize	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchronization, **reduced dose to user**, improved ion source, power supply size, **isotropy issue at distance**, low energy D-D D-T not ideal at distance	6.1	1	1	8	6	Power supplies size
Neutron Source	Characterize	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	2	3	5	3	
Other Source	Characterize	Muon source, photon source...		Sources for interrogation other than neutron and photons. Suggest studies for trade off between different methods, distances relevant for particular ConOps	6.0	1	1			Muon x-ray, charged particle, etc. go to S&O for review

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Appendix D: Data for Requirement 3—Detect Shielded Plutonium

The data in the **Table D1** was collected in the roadmap process for the identification of technologies to address Requirement 3 (Shielded Plutonium Detection). These data are organized by ConOp, Technical Area, and Technical Class. The data include Shortfalls or characteristics desired of passive detection systems. Items that appear in bold type are deemed to be the most important feature. The additional shortfalls or characteristics imposed by active interrogation are included in a separate column. The maturity of the technology uses the DoD 6.0–6.3 rankings. Technical risk is ranked high = 1, medium = 2, and low = 3. Impact is ranked high = 1, medium = 2, and low = 3. (Maturity, risk, and impact are defined in the Technology Assessment by Requirement section.) Estimated target funding per year is given in millions of dollars, and the time required for development to demonstration is provided in years. The enabling technology requirements column provides the working groups assessment of the additional needs for enabling technology R&D to support the more complete development required in that technology class to meet the requirements of the mission program.

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (c

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Search	Large-area detectors—thermal	Large area ($1 m^2$), **high efficiency**, background discrimination, low weight, conformal, **high gamma discrimination**; **transportable** ^3He **tube replacement**, enhanced pulse-shape discrimination desirable	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.2	3	1	1	3	
Neutron Correlation	Search	Large-area detectors—high energy	Large area ($1 m^2$), **high efficiency**, background discrimination, low weight, conformal, **high gamma discrimination**; **transportable** ^3He **tube replacement**, enhanced pulse-shape discrimination desirable	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	2	6	New detectors, less toxic/flammable
Neutron Correlation	Search	Solid-state Neutron detectors	Deployable system design, **must be person portable**, 100 cm^2 detector volume or larger, **high efficiency**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	1	3	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Search	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Real-time readout, recovery	6.1	2	2	1	3	
Neutron Correlation	Search	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Correlation	Contain/Screen	Solid-state Neutron detectors	**Direct detection of high-energy neutrons**, deployable, mobile, large area (1 m^2), high **efficiency, good** gamma discrimination	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	1	3	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Contain/Screen	Large-area detectors—thermal	Large area (1 m^2), **high efficiency**, background discrimination, low **weight**, conformal, high gamma discrimination; transportable ^3He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.2	3	1	1	3	New detector materials required
Neutron Correlation	Contain/Screen	Large-area detectors—high energy	Large area (1 m^2), **high efficiency**, background discrimination, **low weight**, conformal, high gamma discrimination; transportable ^3He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	2	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Contain/ Screen	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Real-time readout, fast recovery	6.1	2	3	1	3	
Neutron Correlation	Contain/Screen	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Correlation	Characterize	Solid-state neutron detectors	**Direct detection of high-energy neutrons**, deployable, mobile, large area (1 m^2), high **efficiency, good** gamma discrimination	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	1	2	3	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics— Passive	Shortfalls/ Characteristics— Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Correlation	Characterize	Large-area detectors—thermal	Large area (1 m^2), **high efficiency**, background discrimination, low **weight**, conformal, high gamma discrimination; transportable ^{3}He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.2	3	1	1	3	
Neutron Correlation	Characterize	Large-area detectors—high energy	Large area (1 m^2), **high efficiency**, background discrimination, **low weight**, conformal, high gamma discrimination; transportable ^{3}He tube replacement	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	2	6	Improved detectors, new detector materials, better light collection/conversion, electronic contacts on semiconductors...
Neutron Correlation	Characterize	Alternate neutron detectors	High sensitivity, **must be nonintegrating**, can be extremely inexpensive, currently very insensitive to gammas	Real-time readout, fast recovery	6.1	2	3	1	3	
Neutron Correlation	Characterize	Neutron detection—timing, multiplicity, signatures	Good gamma discrimination, ns–μs timing capability, large solid-angle coverage: ability to exploit **neutron and gamma correlated signatures**	Fast gating, high stability, reduced radiation damage, activation issues in materials/detectors	6.1	2	1	3	9	New analysis, correlated signatures neutrons and gamma fission signatures
Neutron Spectroscopy	Search	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Spectroscopy	Contain/Screen	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	3	3	9	
Neutron Spectroscopy	Characterize	Neutron spectroscopy systems	**Good energy resolution, high efficiency**, good gamma neutron discrimination, rate limits, broad energy range, low weight, kinematic methods preferred over moderator designs (i.e., Bonner sphere)	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	2	3	9	

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Spectroscopy	Characterize	Ultra high-resolution neutron spectrometry	Must reduce size, need high efficiency, ability to tolerate high rates, increased deployability, **rapid sample change capability**	N/A	6.1	2	3	1	6	
Neutron Imaging	Search	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	2	3	9	
Neutron Imaging	Search	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.3	2	2	1	3	
Neutron Imaging	Contain/ screen	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	2	3	9	
Neutron Imaging	Contain/ screen	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.3	2	2	1	3	
Neutron Imaging	Characterize	3D neutron tracking detector	**Full kinematic reconstruction**, good image quality, **high efficiency**, gamma and neutron discrimination, high rate limits, detect non-thermal neutrons	Fast gating, high rate capability, good stability, activation issues (neutron probes, scintillator detectors)	6.1	2	1	3	9	
Neutron Imaging	Characterize	Neutron imaging detectors	Thermal imagers have been demonstrated, need **large area**, low weight, improved **deployability, should be robust**	Fast gating, high rate capability	6.3	2	1	1	3	
Gamma Correlation	Search	Gamma detection—timing, multiplicity, signatures	Timing capability from ns–μs, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	1	3	6	PSD, high-*Z* loading...

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Gamma Correlation	Contain/Screen	Gamma detection—timing, multiplicity, signatures	Timing capability from ns to μs, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	1	3	6	PSD, high-*Z* loading...
Gamma Correlation	Characterize	Gamma detection—timing, multiplicity, signatures	Timing capability from ns to μs, exploit **correlated gamma and neutron signatures**, high efficiency, large area, good gamma neutron discrimination, integrated neutron and gamma detection desirable	Fast gating, high rate capability, afterglow issues for materials	6.1	2	1	3	6	PSD, high-*Z* loading...
Gamma Spectroscopy	Search	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT
Gamma Spectroscopy	Search	Algorithms for ID in active systems		Time sequence analysis of spectra, Identification of short lived fission and activation products	6.1	1	3	2	6	Measure decay scheme data S&O
Gamma Spectroscopy	Contain/Screen	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT
Gamma Spectroscopy	Contain/ screen	Algorithms for ID in active systems		Time sequence analysis of spectra, Identification of short lived fission and activation products	6.1	1	3	2	6	Measure decay scheme data S&O

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Gamma Spectroscopy	Characterize	High-resolution gamma-ray detectors	**Room-temp. gamma spectrometer approaching HPGe energy resolution**, small system size, reduced system weight, good neutron discrimination, affordability, robust, exploit better photon conversion technologies	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	9	New materials, semiconductor, scintillator, Si photo diodes, light collection, PMT, NRF signatures
Gamma Spectroscopy	Characterize	Algorithms for ID in active systems		Time sequence analysis of spectra, Identification of short lived fission and activation products	6.1	1	3	2	6	Measure decay scheme data S&O
Gamma Imaging	Search	Mechanically collimated systems	Advance designs for **high energy resolution** and dynamic range, improved image quality	Source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow materials	6.2	2	2	1	3	
Gamma Imaging	Search	Distributed sensor systems	Low per unit cost, **interoperability**, **algorithms to exploit collective data**, light weight, robust, imaging or non imaging systems individual sensors		6.1	1	3	8	9	Metadata analysis from radiation detectors, communication available in industry not a research issue
Gamma Imaging	Search	Electronically collimated system	**Large active volume**, high efficiency, medium to high energy resolutions, reduced complexity, reduce cost, **field deployment capable, ease of use**	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	2	10	6	ASIC development, gamma spectroscopy materials
Gamma Imaging	Contain/Screen	Electronically collimated system	Large active volume, **high efficiency**, medium to high energy resolutions, reduced complexity, reduce cost	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	2	10	6	ASIC development, gamma spectroscopy materials
Gamma Imaging	Contain/Screen	Mechanically collimated systems	Advance designs for **high energy resolution** and dynamic range, improved image quality	Source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow materials	6.2	2	2	1	3	

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Gamma Imaging	Contain/Screen	Distributed sensor systems	Low per unit cost, **interoperability**, **algorithms to exploit collective data**, light weight, robust, imaging or non imaging systems individual sensors		6.1	1	2	8	9	Metadata analysis from radiation detectors, communi-cation available in industry not a research issue
Gamma Imaging	Characterize	Mechanically collimated systems	Advance designs for **high energy resolution** and dynamic range, improved image quality	Source discrimination, fast gating, high rate capability, tolerance to radiation damage, reduced afterglow materials	6.2	2	1	1	3	
Gamma Imaging	Characterize	Electronically collimated system	Large active volume, **high efficiency**, medium to high energy resolutions, reduced complexity	Fast gating, high rate capability, reduced radiation damage to materials, matrix composition damage, afterglow for materials, requires large dynamic range detectors	6.1	1	1	10	6	ASIC development, gamma spectros-copy materials
Gamma Imaging	Characterize	Distributed sensor systems	Low per unit cost, **interoperability**, **algorithms to exploit collective data**, light weight, robust, imaging or non imaging systems individual sensors		6.1	1	3	8	9	Metadata analysis from radiation detectors, communi-cation available in industry not a research issue
Photon source	Search	Broad spectrum		Good collimation, high end-point energy, high flux, pulsed for (photo fission), DC for NRF, selectable energy end point, **light weight**, low energy consumption, **reduced dose to user,** beam hardened**,** beam manipulation capability	6.2	3	2	8	6	Driven by industry
Photon source	Search	Mono-energetic		**Forward directed**, good collimation, high energy, **high flux**, pulsed (photo fission), DC (NRF), **tunable energy (LCS), selectable energy (re-action based sources)**, light weight, low energy consumption, reduced dose to user, beam manipulation	6.1	1	2	20	9	Compact high power laser

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics— Passive	Shortfalls/ Characteristics— Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Photon Source	Contain/Screen	Broad spectrum		**Good collimation**, high end-point energy, high flux, pulsed for (photo fission), DC for NRF**,** selectable energy end point, light weight, low energy consumption, **reduced dose to user,** beam hardened**,** beam manipulation capability	6.2	3	2	8	6	Driven by industry
Photon Source	Contain/Screen	Mono-energetic		**Forward directed**, good collimation, high energy, **high flux**, pulsed (photo fission), DC (NRF), **tunable energy (LCS), select-able energy (reaction based sources)**, light weight, low energy consumption, reduced dose to user, beam manipulation	6.1	1	2	20	9	Compact high power laser
Photon Source	Characterize	Broad spectrum		**Good collimation**, high end-point energy, high flux, pulsed for (photo fission), **DC for NRF,** selectable energy end point, light weight, low energy consumption, reduced dose to user**, beam hardened,** beam manipulation capability	6.2	3	2	8	6	Driven by industry
Photon Source	Characterize	Mono-energetic		**Forward directed**, good collimation, high energy, **high flux**, pulsed (photo fission), DC (NRF), **tunable energy (LCS), select-able energy (reaction-based sources)**, light weight, low energy consumption, reduced dose to user, beam manipulation	6.1	1	2	20	9	Compact high power laser

Table D1. Requirement 3—Detect shielded plutonium R&D by technology data by ConOp. (cont.)

Technical Area	ConOp	Technology Class	Shortfalls/ Characteristics—Passive	Shortfalls/ Characteristics—Active	Maturity	Technical Risk	Impact	$M/yr	Years to Demonstration	Enabling Technology Requirements
Neutron Source	Search	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchronization, **reduced dose to user,** improved ion source, power supply size	6.1	2	2	8	6	Power supplies size
Neutron Source	Search	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	2	2	5	3	
Neutron Source	Contain/Screen	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchronization, **reduced dose to user,** improved ion source, power supply size	6.1	2	2	8	6	Power supplies size
Neutron Source	Contain/Screen	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	3	2	5	3	
Neutron Source	Characterize	Accelerator based		**High flux**, tunable energy, duty cycle, robust, long lifetime, **directional**, short pulse, synchronization, **reduced dose to user,** improved ion source, power supply size	6.1	2	2	8	6	Power supplies size
Neutron Source	Characterize	Radioactive source based		**On-off capability**, **high flux**, robust, **portable**, compact, low dose in off state, ability to provide synchronization with detectors, safety, good directionality	6.2	3	2	5	3	
Other Source	Characterize	Muon source, photon source...		Sources for interrogation other than neutron and photons.	6.0					Muon x-ray, charged particle, etc go to S&O for review

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Appendix E: Acronyms and Abbreviations

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
APD	avalanche photodiode
ASIC	Application-specific integrated circuit
CMOS	Complementary metal oxide silicon
ConOp(s)	Concept of Operation(s)
COTS	Commercial off-the-shelf
CPG	Coplanar grid (detector)
CsI(TI)	Thallium-doped cesium iodide
CW	Continuous wave
CZT	Cadmium zinc telluride
DHS	Department of Homeland Security
DNDO	Domestic Nuclear Detection Office, a Department of Homeland Security office
DoD	Department of Defense
DOE	Department of Energy
DU	Depleted uranium
FPGA	Field-programmable gate array
FWHM	Full-width half-maximum
FY	Fiscal year
HEU	Highly enriched uranium
HPD	Hybrid photodiodes
HPGe	High-purity germanium
JFET	Junction gate field-effect transistor
MOSFET	Metal-oxide semiconductor field-effect transistor
NA-22	Office of Nonproliferation Research and Development
NaI(TI)	Thallium-doped sodium iodide
NASA	National Aeronautics and Space Administration
NCRP	National Council for Radiation Protection
NDD	Nuclear Detonation Detection (program)

NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
NRF	Nuclear resonance fluorescence
OCONUS	Outside the Continental United States
PART	Program Assessment Rating Tool
PDP	Proliferation Detection Program
PMT	Photomultiplier tube
PSD	Pulse shape discrimination (detector)
PVT	Poly-vinyl toluene
R&D	Research and development
RDT&E	Research, development, test, and evaluation
RFQ	Radio frequency quadrupole
RHESSI	Reuven Ramaty High-energy Solar Spectroscopic Imager
RIID	Radioisotope identifier
SiPMT	Silicon photomultiplier tubes
SNM	Special nuclear material
TPC	Time projection chamber
TRL	Technology Readiness Level

Office of High Energy Physics Accelerator R&D Task Force Report

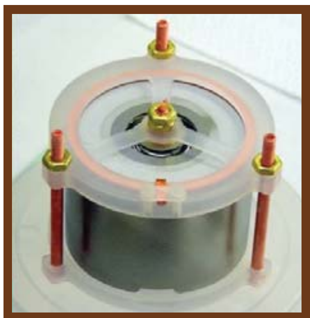
Appendix 14

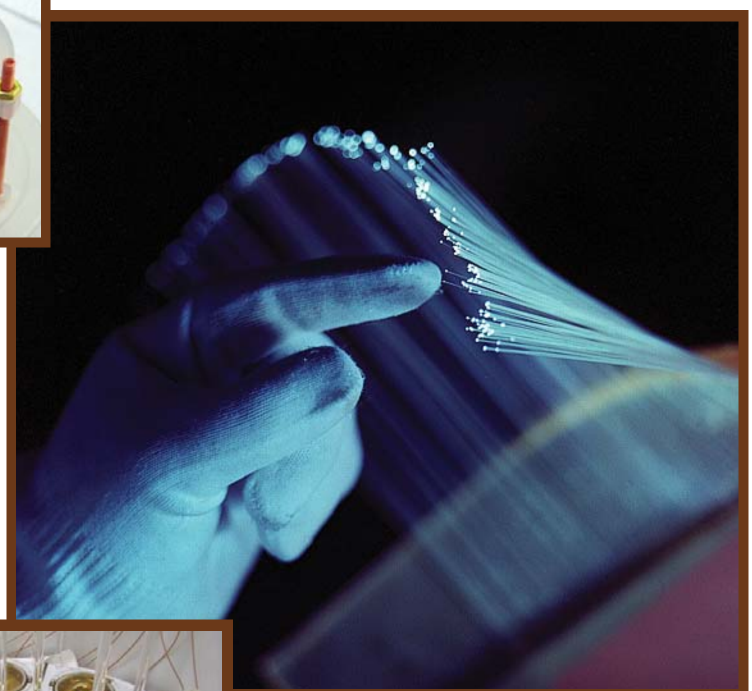
National Nuclear Security Administration – Radiation Sensors and Sources Roadmap

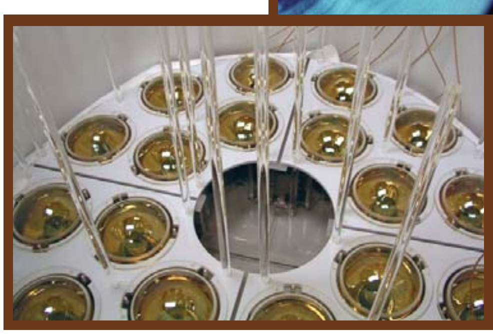
National Nuclear Security Administration
NA22-OPD-01-2010

Special Nuclear Materials Movement Detection Program

Radiation Sensors and Sources Roadmap

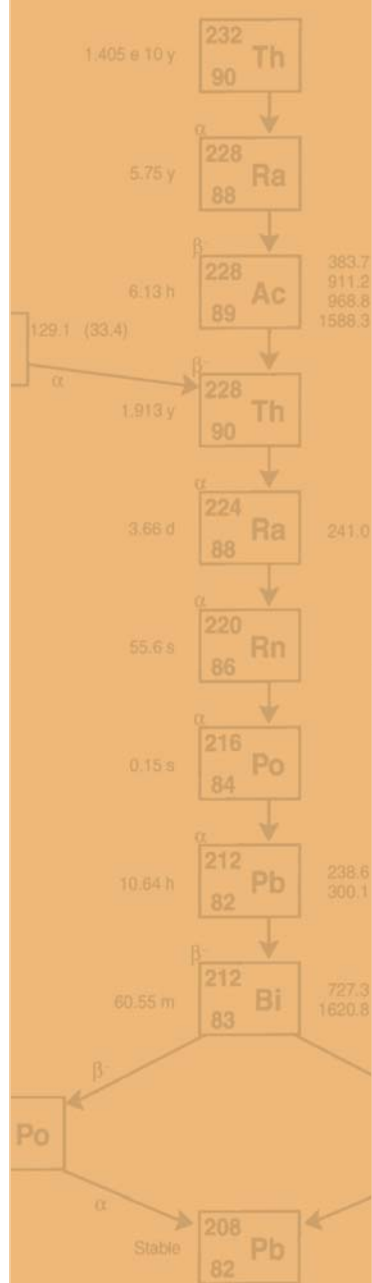






October 2009

Office of Nonproliferation and Verification Research and Development (NA-22)



On the Cover

Top:
High-purity germanium is a mature technology for high-resolution measurements of special nuclear materials.

Middle:
Lithium-doped scintillating glass optical fibers are a viable medium for large-area, solid-state, thermal neutron sensors.

Bottom:
Water Cerenkov detectors doped with trace quantities of ^{10}B and ^{157}Gd rely on photo-detection of Cerenkov radiation created by gamma-ray emissions from neutron capture agents held in a water solution.

Comments and inquiries regarding this document should be directed to Dr. Edward Watkins, NNSA/NA-22 at 202-586-6609 or Dr. Robert Runkle, NNSA/NA-22 at 202-586-5118.

Acknowledgements

Working Group Members

To better focus the research and development efforts of the Special Nuclear Material (SNM) Movement Detection Program within NA-22, an expert working group was assembled to establish a technical roadmap for this program. This working group consisted of technical and programmatic representatives from across the Department of Energy complex. The working group contributed to all phases of this document's development by contributing and editing text, leading workshops, and providing technical and programmatic input to NA-22. The members of the working group are:

Zane Bell, Oak Ridge National Laboratory
Adam Bernstein, Lawrence Livermore National Laboratory
Brandon Blackburn, formerly of Idaho National Laboratory
John Goldsmith, Sandia National Laboratories
Ralph James, Brookhaven National Laboratory
Rob Johnson, Lawrence Berkeley National Laboratory
James Jones, Idaho National Laboratory
Jim Lund, Sandia National Laboratories
Karl Pitts, Pacific Northwest National Laboratory
Paul Raptis, Argonne National Laboratory
Saleem Salaymeh, Savannah River National Laboratory
Morag Smith, Los Alamos National Laboratory
Susan Turner, Y-12 Security Complex
Jim White, Oak Ridge National Laboratory
Quang Jen Wu, Lawrence Livermore National Laboratory

Subject Matter Experts

Critical to the development of this document was the solicitation of input from subject matter experts across a variety of disciplines. This input formed the basis of this document, the *Radiation Sensors and Sources Roadmap*. The group convened in early 2008 for a three-day meeting to gather input, which primarily consisted of the identification of research and development investment options. The group consisted of subject matter experts from across the Department of Energy complex and academia. These subject matter experts, listed by section, are:

Photon Detection Systems
Glenn Knoll, University of Michigan
Ed McKigney, Los Alamos National Laboratory
Paul Raptis, Argonne National Laboratory
Saleem Salaymeh, Savannah River National Laboratory
Eric Smith, Pacific Northwest National Laboratory
Morag Smith, Los Alamos National Laboratory
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Q1010

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Rob Johnson, Lawrence Berkeley National Laboratory
Ka-Ngo Leung, formerly of Lawrence Berkeley National Laboratory
Bernhard Ludewigt, Lawrence Berkeley National Laboratory
Karl Pitts, Pacific Northwest National Laboratory

In addition, a set of peer reviewers, who did not contribute to the roadmap's formulation, was charged with assessing the technical accuracy in each topic area. This group consisted of:

Lorenzo Fabris, Oak Ridge National Laboratory
Kristin Hertz, Sandia National Laboratories
Dean Mitchell, Sandia National Laboratories
Anthony Peurrung, Pacific Northwest National Laboratory
Doug Wells, Idaho State University/Idaho Accelerator Center

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Office of Nonproliferation and Verification
Research and Development (NA-22)
Publication Release Form

Special Nuclear Materials Movement Detection Program—
Radiation Sensors and Sources Roadmap

My signature indicates that I have reviewed and approved for unlimited release within the nonproliferation community the *Special Nuclear Materials Movement Detection Program—Radiation Sensors and Sources Roadmap*, NA22-OPD-01-2010.

This document prioritizes specific investment options for achieving the requirements outlined in the *Special Nuclear Materials Movement Detection Portfolio—Technology Roadmap*, NA22-PDP-02-2007.

Dr. T. Jan Cerveny
Assistant Deputy Administrator
Office of Nonproliferation and Verification Research and Development

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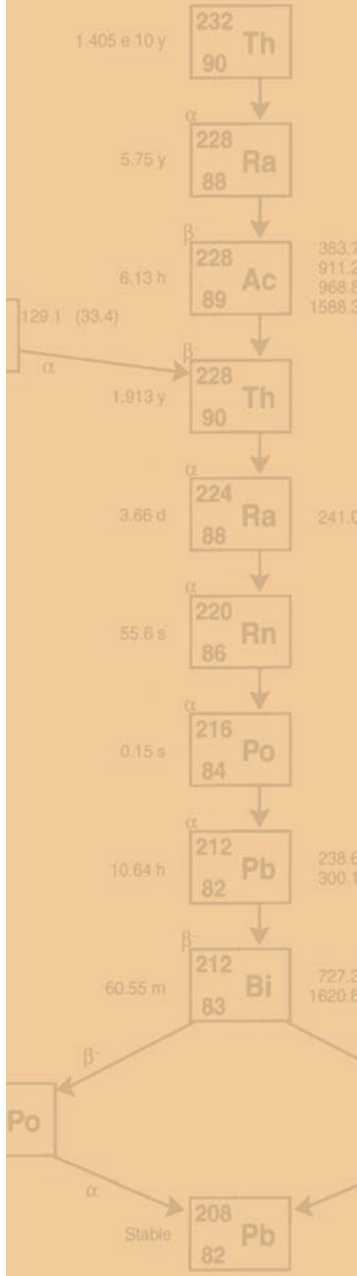

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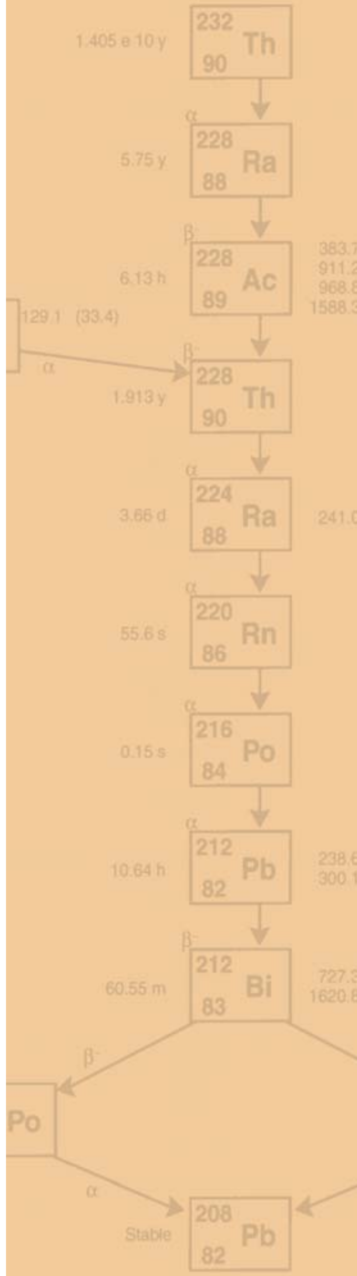


Executive Summary

The Office of Proliferation Detection (NA-221) within the National Nuclear Security Administration's (NNSA) Office of Nonproliferation and Verification Research and Development (NA-22) has established a multi-year strategy in the form of program plans and roadmaps to conduct the research and development (R&D) necessary to demonstrate next-generation special nuclear materials (SNM) movement detection technologies. This strategy sets an ambitious schedule to plan, execute, and demonstrate mission-relevant components and technologies for SNM detection. As established in the 2006 strategic document, *SNM Movement Detection Portfolio—Goals, Objectives, and Requirements*, the high-level program requirements are:

- Detect shielded highly enriched uranium (HEU)
- Detect SNM at standoff distances
- Detect shielded weapon-grade plutonium

These requirements directly target the development of high-impact technologies for nuclear material detection that are applicable to nuclear nonproliferation applications including material monitoring, interdiction, and verification, as well as counterproliferation and counterterrorism, where synergies exist.

The SNM Movement Detection Program then created a technical roadmap, the *SNM Movement Detection Portfolio—Technology Roadmap* in 2007 that identified and prioritized high-level technology classes for R&D. That document articulated the priorities of the SNM Movement Detection Program to other agencies internal and external to the Department of Energy. This document, the *Radiation Sensors and Sources Roadmap*, further defines and prioritizes investments in specific R&D topics that support NA-22's needs in the areas of radiation sensors and sources. It portends to facilitate communication with the national laboratory, academic, and small-business communities that have been tasked to perform long-term R&D.

The SNM Movement Detection Program assembled an expert technical and programmatic working group consisting of subject matter experts (SMEs) from across the Department of Energy's national laboratory complex. Their task was to define the state-of-the-art and important new directions for research necessary to ensure progress toward the program requirements. Additionally, this working group leveraged input and recommendations from over 50 scientists and engineers from the Department of Energy national laboratories and academia. With this input, the working group and NA-22 staff developed a methodology to organize and analyze the collected data. This methodology prioritizes relevant R&D options within five technical areas:

- Photon detection systems
- Neutron detection systems
- Imaging methods
- Photon sources
- Neutron sources

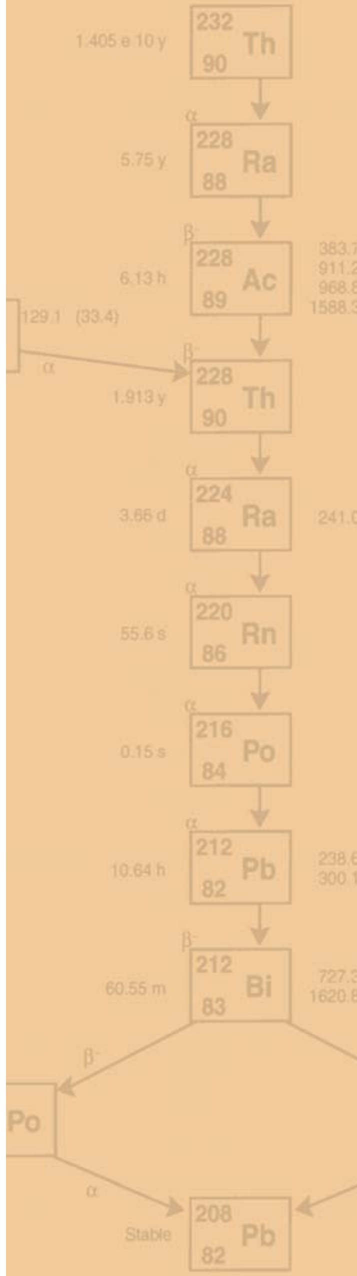
Executive Summary

The SNM Movement Detection Program developed the following criteria to guide its investments. Options within each technical area were chosen based on their ability to: (a) emphasize revolutionary over evolutionary approaches, (b) give greater importance to lower-maturity R&D areas that are likely to produce greater advances in detection capability with long-term investments, and (c) assign greater importance to R&D areas that provide the most impact across all three program requirements. The program prioritized investment options first according to the priority of the associated technical class from the *SNM Movement Detection Portfolio—Technology Roadmap,* and then by their anticipated impact. The prioritization, listed in **Table ES-1**, is the result of this effort. Only those investment options that received a high priority rating or those with a medium priority but high impact rating are listed. Many other investment options were considered during the roadmap process.

Table ES-1. Long-term investment option priorities chosen to support the R&D priorities established in the *SNM Movement Detection Portfolio—Technology Roadmap*.

Priority	Impact	Topic Area	Investment Option
High	High	Photon detection systems	Alternate radiation detection and readout concepts
			Spectroscopy algorithms for signal-starved spectra
		Neutron detection systems	Large-area, thermal neutron detection systems
			Algorithm development for exploitation of time-correlation observables
			Large-area, fission neutron detection systems
		Photon sources	Next-generation accelerator concepts
			Low-energy, monoenergetic, tunable sources
			Development of compact, mobile photon sources
		Neutron sources	Next-generation ion sources
			Robust, human-portable systems
			Directional beams of high-energy neutrons
	Medium	Photon detection systems	Assess deployment feasibility of proven non-traditional radiation detectors
			New strategies for charge collection in semiconductors
			Stable, solid-state readout technology for scintillators
			Detection limit mapping
		Neutron detection systems	Measurements and phenomenological modeling of SNM fission signatures
			Measurements and phenomenological modeling of cosmic-ray induced neutron backgrounds
		Photon sources	Development of high-energy, quasi-monoenergetic sources
			High-repetition-rate LINACs
		Neutron sources	Transportable, high-flux sources
			Scenario definition for standoff applications
			Advances in time-tagged neutron sources
Medium	High	Photon detection systems	Algorithms for active interrogation signatures exploitation
		Neutron detection systems	Solid-state thermal neutron detection systems
		Imaging methods	Imaging systems not reliant on segmentation/modulation
			Scatter cameras that track secondary particle production
			Simultaneous gamma-ray and neutron imaging
			Single-crystal, high-energy neutron imaging systems

Introduction



The Office of Proliferation Detection (NA-221) has established a multi-year strategy in the form of program plans and roadmaps to conduct the research and development (R&D) necessary to demonstrate next-generation nuclear nonproliferation technical capabilities and component technologies. These strategies set an ambitious schedule to plan, execute, and evaluate the R&D necessary to demonstrate new capabilities.

This effort represents the culmination of a process that began in 2006 with the collection of capability requirements from users across the nonproliferation community. User input was an integral part of the goals, objectives, and requirements documents developed for the NA-221 mission programs, including Special Nuclear Material (SNM) Movement Detection, U-235 Production Detection, and Pu Production Detection. Following the completion of the *SNM Movement Detection Portfolio—Goals, Objectives, and Requirements* document (NA-22-PDP-03-2006), the SNM Movement Detection Program then created a technical roadmap, *SNM Movement Detection Portfolio—Technology Roadmap* in 2007, which identified and prioritized technology classes in need of R&D. This document—the *Radiation Sensors and Sources Roadmap*—further defines and prioritizes investments in specific R&D topics that support NA-22's needs in the areas of radiation sensors and sources. The goal of this document is to facilitate communication by clearly stating NA-22's specific R&D priorities with the national laboratory, university, and small-business communities.

Overview

The Office of Proliferation Detection consists of eleven R&D programs that are grouped by mission areas, enabling technologies, and signatures and observables, as illustrated in **Figure 1**. It applies the unique skills and capabilities of the NNSA and Department of Energy national laboratories and facilities to meet the R&D needs to close technology gaps identified through close interaction with other U.S. Government agencies and in support of U.S. Government policy. It also draws upon the talents and strengths of the academic community and industry to complement the national laboratories, where appropriate, and develops the tools, technologies, techniques, and expertise to address the most challenging problems related to detection, localization, and analysis of the global proliferation of weapons of mass destruction, with special emphasis on nuclear weapon technology and SNM diversion. Additionally, NA-221 funds limited research that supports counterproliferation and counterterrorism where there is synergy with the nonproliferation mission.

Introduction

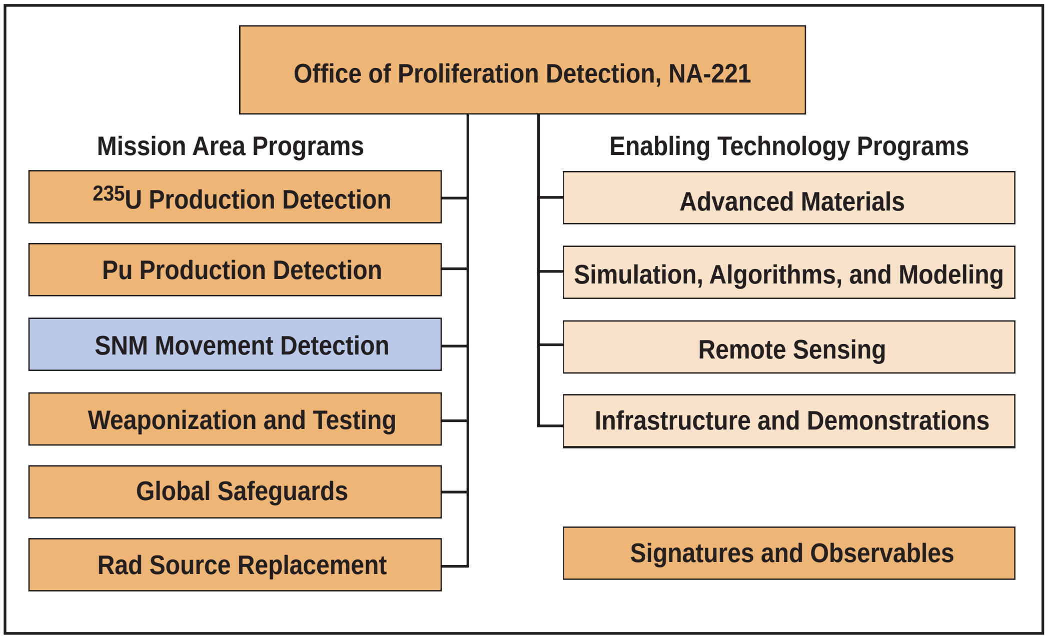


Figure 1. NA-221 Office of Proliferation Detection organization.

NA-221 plays a key role in filling the critical middle ground between fundamental research and near-term systems development by using the unique capabilities of the national laboratories to conduct basic and applied research and technology integration. Through the extensive relationships that national laboratories maintain with universities, basic science from academia and federal research programs are brought together to develop real-world system solutions based on insights into national security problems. NA-221 delivers technical know-how that has been developed and validated to U.S. Government acquisition programs and the U.S. industrial base to support national security missions. Technical advances, new proven methodologies, and improvements to capabilities are transferred to operational programs through technical partnerships, including development of special demonstration apparatus to assist major acquisition efforts.

NA-221 provides long-term emphasis and support for a broad spectrum of technology areas predominantly considered to be at the applied research and advanced applied research levels of development. In the characterization of technical maturity defined by the Department of Defense (DoD) Research, Development, Test, and Evaluation (RDT&E) or Technology Readiness Levels (TRLs), this program focuses upon technologies at the RDT&E Level 6.1 and 6.2 or TRL 1–5. These levels of technical maturity correspond to developing a concept, performing basic research, and performing research to demonstrate the proof of principle. In some rare instances, and only after consultation with a specific end-user, a technology development project may be taken through a formal demonstration stage of development (TRL 6–7). NA-22 may occasionally provide for field-testing a particular technology, but developing a fieldable demonstration prototype is in partnership with a specific end-user.

The purpose of the SNM Movement Detection Program is to conduct early stage R&D that supports the broad missions of NA-22, including SNM monitoring, interdiction, and verification. The SNM Movement Detection Program funds R&D to improve the spatial, energy, and time resolution of both gamma-ray and neutron detection methods applicable to nuclear nonproliferation problems. Typical investments in this program focus on improving electronics and other components necessary to efficiently readout the detectors, developing novel detection techniques, and improving existing techniques. R&D conducted in this program will have broad applicability to the radiation detection community at large, but requirements are derived its requirements from the mission programs of the NA-22 office.

Scope

The *Radiation Sensors and Sources Roadmap* is the third document in a series that establishes the SNM Movement Detection Program's goals and milestones, which are listed in **Table 1**. In 2006, an expert working group developed the first document, entitled *Special Nuclear Materials Movement Detection Portfolio—Goals, Objectives, and Requirements*, NA-22-PDP-03-2006, which defined the requirements for the SNM Movement Detection Program as:

- Detect shielded highly enriched uranium (HEU)
- Detect SNM at standoff distances
- Detect shielded weapon-grade plutonium

These high-level requirements form the basis for this long-term proliferation detection R&D program within NA-22. The second document, the *SNM Movement Detection Portfolio—Technology Roadmap*, NA22-PDP-02-2007, identified and prioritized technology classes in need of R&D to meet the aforementioned requirements. **Table 2** lists these technology classes and their priority levels. The *SNM Movement Detection Program—Technology Roadmap* articulated priorities of the SNM Movement Detection Program to other agencies internal and external to the Department of Energy.

Table 1. Program Assessment Rating Tool (PART) requirements for the SNM Movement Detection Program.

Year	PART Requirement for SNM Movement Detection
2006	Complete general goals, objectives, and requirements
2007	Complete SNM movement detection roadmap
2009	Complete initial technical feasibility studies for alternative technology approaches
2010	Complete external expert/user review and ranking
2011	Complete ranking of alternative approaches and down-selection process
2012	Complete research phase on selected approaches
2013	Demonstrate developed technologies and methods

Table 2. R&D priorities established in the *SNM Movement Detection Portfolio—Technology Roadmap*.

Topic Area	R&D Technology Class	Priority Level
Photon detection systems	High-resolution gamma-ray detectors	High
	Gamma detection—timing, multiplicity, signatures	High
	Algorithms for ID in active systems	Medium
Neutron detection systems	Neutron detection—timing, multiplicity, signatures	High
	Large-area detectors—high-energy	High
	Solid-state neutron detectors	Medium
	Large-area detectors—thermal	Low
Imaging methods	3-D neutron tracking detector	Medium
	Electronically collimated systems	Medium
	Mechanically collimated systems	Low
	Neutron imaging detectors	Low
Photon sources	Broad spectrum	High
	Monoenergetic	High
Neutron sources	Accelerator based	High
	Radioactive source based	Low

The *Radiation Sensors and Sources Roadmap* identifies and prioritizes specific R&D investment options within the context of past and ongoing work. The roadmap process and its product (this document) seek to define a set of investments to address the gaps identified in the current state of the art, leading the program closer to meeting its long-term R&D goals. This roadmap is thus a technical guide to the Radiation Sensors and Sources Program and can be used to identify topics for yearly proposal solicitations, guide the selection of proposals, and establish priorities for program budgets by:

- Comparing technology development pathways, as identified in this document, with currently supported R&D efforts in order to develop a program investment strategy.
- Identifying shortfalls or technology gaps in pathways that can be used as the basis for future R&D.
- Defining the guiding principles of a program investment plan for meeting program requirements by 2013 and beyond.
- Serving as a communication tool between NA-22 and the national laboratory, academic, and small-business R&D communities.

The dynamic international proliferation environment and the potential for the rapid emergence of new technical challenges and technological developments may subject this document to regular revision, for example in the case of anticipated treaty verification requirements. The intent is to periodically convene a working group to review the continued relevance of this document and, where necessary, make recommendations for modification.

Introduction

This document is the culmination of significant effort on the part of a number of contributors including a working group augmented by a subject matter expert group that supplied technical input and advice. The formulation followed the general outline set forth in the *SNM Movement Detection Portfolio—Technology Roadmap*. Beginning with the prioritized technology classes defined in Table 2, this document divides technology development space into five broad topic areas—Photon Detection Systems, Neutron Detection Systems, Imaging Methods, Photon Sources, and Neutron Sources.

Data for the development of this roadmap were collected by the working group during an intensive three-day workshop with the SMEs. The layout of this document follows the data collection process that was structured as follows:

- **Technology Requirements.** Each group validated the prioritized technology classes for their technology area and identified any additional needs for R&D that would be required to meet the program goals. The groups discussed how the results from the *SNM Movement Detection Portfolio—Goals, Objectives, and Requirements* applied to their technical area. This discussion set the scope for each group and their subsequent efforts.
- **Survey of Field.** The SMEs described the current state of the art for their technical area including a broad survey of ongoing R&D. This survey sets a starting point for any future investments in R&D in each respective field.
- **Identification of Shortfalls.** The SMEs then identified gaps between the program's requirements (goals) and the current state of the art (starting point). These shortfalls take the form of specific R&D scope necessary to meet the program's requirements.
- **Investment Options.** The SMEs then identified R&D options that, if successful, would fill the identified technology shortfalls. For each potential solution, the group provided the relative impact, current maturity, risk of failure, cost to complete, and time necessary to complete the R&D needed to realize the solution. The impact was characterized as high—will significantly advance the state of the art toward the goal; medium—will provide moderate advances in the state of the art toward the goal; or low—will provide minimal advancement toward the goal.

Following completion of the workshop, NA-22 evaluated the technology requirements, current state of the art, shortfalls, and potential investment options. Based on the prioritized technology classes established in the roadmap and anticipated impact levels for each investment option, NA-22 independently prioritized the list of investment options to form a program plan. This document summarizes that plan.

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Photon Detection Systems

Technology Requirements

Application of photon detection systems to SNM movement detection spans many methods from compact, mobile, low-power passive systems to large-scale, fixed-site, active-interrogation systems. This expansive application space imposes a wide and varying range of requirements on the photon detection components of the various overall detection systems. For example, some applications require fast detectors to exploit time coincidence measurements, while others require high precision in the determination of the incident gamma-ray energy; in essentially all applications, the role of photon detection systems is to further four generic goals:

- *Detection*—The simplest form of photon measurement is the use of a detector to count gamma rays. Gross counting can flag the presence of radioactive material, which could be SNM. Gamma-ray spectroscopy can exploit more sophisticated signatures to provide higher detection performance.
- *Location*–Photon detection systems can provide location information via either proximity search, where a non-directional detector is moved through space, or via systems specifically designed to provide directional information. These systems will be addressed separately in the *Imaging Methods* section.
- *Identification*—Gamma-ray spectroscopy provides the capability to identify constituent isotopes in an energy spectrum if sufficient fidelity is provided. This creates the capability to differentiate SNM from other radioactive materials, as well as determining the detailed isotopic composition of the SNM itself. In some applications, it is desirable to distinguish between enrichment levels or between weapon-grade and reactor-grade materials.
- *Characterization*—Photon detection can be used to determine attributes of the radioactive material such as mass and activity. Analysis of the full-energy spectrum of medium- and high-resolution data can be used to estimate the density and atomic number of intervening material between the source and the detector, as well as self shielding from the SNM itself. The nature of the fission process allows for the possibility of exploiting correlations between gamma rays, gamma rays and neutrons, and gamma rays and interrogating particles to further characterize fissionable material, including mass and neutron multiplication.

No one set of requirements can be specified to achieve all these goals within the entire application space, and there is likely no application that imposes all of them, but the following qualitative requirements broadly capture the overall needs.

Absolute collection efficiency is often the dominant figure of merit of a photon detector, and the interrelation between absolute detection efficiency, material size, and cost must be part of any design trade-off. Detectors with high energy resolution tend to be expensive per unit volume and thus have limited absolute collection efficiency for a given cost. Even a material with a low intrinsic efficiency can have large absolute collection efficiency if it is inexpensive to manufacture in large volumes. Minimum useful detector sizes are typically of $O(1{,}000\text{–}10{,}000\ cm^3)$* for applications ranging from handheld instruments to portal monitors.

If a detector can meet absolute collection efficiency requirements, then energy resolution, which describes the precision with which the energy deposition of the incident photon can be determined, often becomes the relevant figure of merit. High-resolution gamma-ray detectors, whose development is a first-priority item in the *SNM Movement Detection Portfolio—Technology Roadmap*, enable each of the goals above. Energy resolution is crucial in distinguishing threatening and benign materials, reconstructing directionality from scattering events, mitigating interferences of adjacent peaks when identifying isotopes, and reducing background under full-energy peaks in detector response functions so that the magnitude of emitted fluxes can be precisely calculated. All next-generation photon detectors of interest to this roadmap must provide a high degree of spectroscopic capability. A reasonable target energy resolution for detection systems is 1 percent at 662 keV.

In analogy to energy resolution, time resolution describes the precision with which the arrival time of a measured photon can be determined, and time resolution determines the maximum count rate at which photons can be individually distinguished. These parameters are generally determined by the rise and fall times of detector pulses. For the majority of applications that examine uncorrelated, weak signals, count-rate limits in the thousands of counts per second range are acceptable. Time-correlation measurements, whose application to SNM detection is a first-priority item in the *SNM Movement Detection Portfolio—Technology Roadmap*, impose different measurement constraints. Time-correlation applications can make use of nanosecond resolution, although it is not yet clear what resolution will be required in any particular application. Active interrogation systems present the largest challenges to time resolution due to the massive event rates expected in some cases. Especially in systems using pulsed sources, there may be a need to handle instantaneous rates exceeding one million counts per second.

Essentially all nonproliferation applications require detection systems to be robust, mobile, and field-deployable. Photon detection systems that are suitable and effective for laboratory use may not be usable in field situations where infrastructure and personnel capabilities are limited. The most prominent example is that of high-purity germanium (HPGe), which has seen limited field deployment despite significant advances in cryostat design and mechanical cooling technology. Fielded systems must operate under a wide range of factors including temperature variation, shock, and vibration. Many applications require operation under battery power, and this roadmap document is particularly interested in the development of high-resolution photon detectors that do not consume significant electrical power.

Algorithms play a key role in converting detector-response data into actionable information. Advanced algorithms are required for identification of SNM in field applications where there is a large amount of background “clutter.” Specifically,

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* This document uses the notation “…of *O*” to denote “on the order of.” For example, “an external electric field of *O*(100–1,000 V/m)” means “an external electric field on the order of 100–1,000 V/m.”

algorithms must distinguish SNM from naturally occurring radioactive material, commercial sources, and medical isotopes in both active and passive applications. The algorithms must perform this identification in real time without the assistance of an analyst. This identification must be possible using energy calibrations attainable in the field and must be possible for spectra with a low number of counts. Algorithms operating in active interrogation settings must overcome new challenges associated with the introduction of artifacts from high-event-rate operation. Given the development of active interrogation, the development of algorithms for isotope identification in active interrogation systems was a second-priority item in the *SNM Movement Detection Portfolio—Technology Roadmap*.

Survey of Field

Following discovery and growth of advanced materials, detection media must be converted into detection systems, and this section discusses the methods and tools developed to convert a given material into a photon detection system. The process of integrating radiation-sensitive materials into radiation detection systems can be conceptually divided into three steps. First, the detector material, which may consist of a scintillator, semiconductor, or gas, must be packaged in a manner to meet the competing requirements of detection efficiency, energy resolution, etc. Second, readout technology converts the inherent signal, e.g., scintillation light, into a form suitable for data processing. Third, data analysis algorithms process the readout and translate it into actionable information consistent with the goals of detect, identify, locate, and characterize. Each of these steps may overlap, such as in the case of pulse-shape analysis, which may be integrated into readout technology.

Integration of Materials into Radiation Detectors

Solid Scintillators—Perhaps the most ubiquitous detection materials deployed en masse today are plastic scintillators [Kou05]. Since plastic scintillators are manufactured via dissolution of an organic scintillator into a formable polymer, they have the advantages of procurement in large volumes and many shapes, room-temperature operation, high durability, and low cost. Disadvantages result from their poor energy resolution and general lack of full-energy depositions, sensitivity to neutrons and poor pulse-shape discrimination, reduced light collection when formed into large panels, and low intrinsic efficiency.

The other large scintillator category consists of inorganic crystals. Slow inorganics such as NaI are mature technologies with medium resolution (6–10%), moderate cost, and moderate size. They can be somewhat fragile, crack under rapid temperature changes, and usually require shock-mounting. Modest temperature changes routinely encountered in field operation result in gain shifts large enough to require frequent energy calibration [She97]. Some systems contain small embedded sources or light pulsers to continuously measure or control gain shifts associated with the photo-cathode response [Sau05].

The newer lanthanum halides are fast inorganic scintillators with better energy resolution than NaI, in the range of 2–4 percent at 662 keV, but they are still expensive and not yet available in large sizes. Their performance improvement over NaI is limited by non-proportionality effects that are significant at lower energies [Bal05][Dor04]. There may also be a limitation for use in large detectors because of self activity due to the intrinsic natural activity of ^{138}La [Ker06].

Scintillation crystals that are hygroscopic, such as NaI and $LaBr_3$, must be encapsulated. They are typically sealed in a metallic can, coated on the inside with a diffuse reflector, and sealed with a window, which is transparent to scintillation light. Those that are not hygroscopic, such as $CdWO_4$, can be used immediately after polishing. In either case, a reflective coating is usually applied to all surfaces not in contact with the photo sensor.

Liquid Scintillators—Detectors realized in the liquid phase are mostly scintillators that are based on organic phosphors dissolved in hydrocarbon solvents. Organic liquid scintillators share the common requirements of containment and maintenance of an oxygen- and water-free head space in the containment vessel. In the case of hydrocarbon-based scintillators, containment is often an issue because the solvents dissolve or otherwise damage the plastics that might be used for the vessel, necessitating the use of stainless steel, glass, or fused quartz. A glass or quartz window is required for the interface between the vessel and the scintillator, although in some cases it is possible to use a photomultiplier tube's face plate as the interface.

Liquid organic scintillators can be made into large detectors, operate at room temperature, and are less expensive than crystalline scintillators, but still cost more than plastics. Further, they can be used with pulse-shape discrimination techniques, but these show poor performance for neutron energies less than 500 keV [Bel81]. The disadvantages are poor energy resolution (15–30%), large nonlinearities, and a low full-energy-peak fraction. The biggest disadvantages of field use of liquid scintillators are that the typical solvents are toxic and/or flammable and the coefficient of thermal expansion is not negligible. Their primary potential at this time rests in applications where the possibility of detecting gamma rays and neutrons in one detector outweighs fieldability difficulties.

Detectors using liquefied noble gases, which are either refrigerated or at high pressure, have been demonstrated [Kno00]. The detectors are fabricated from ultra-pure gas that is contained in stainless steel or titanium vessels. These devices behave like ionization chambers and offer resolution similar to that obtained with CZT and $LaBr_3$. Their main drawbacks are the need for refrigeration and/or high pressure and the relatively low density of liquefied gas.

Semiconductors—High-purity germanium (HPGe), shown in **Figure 2**, is a mature technology that serves as the "gold standard" for high-resolution measurements of SNM with its energy resolution of ~0.3 percent at 662 keV and highly linear response. While expensive and of limited size, the primary limitation on field deployment is its need for low-temperature operation. Progress has been made on mechanically cooled systems but, it has come at the expense of energy resolution, although recent work

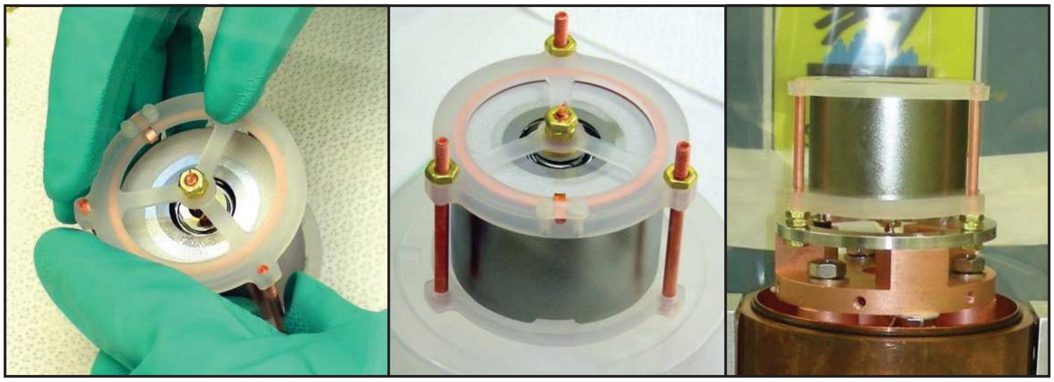

Figure 2. Photographs of high-purity germanium crystal assembly including insulator (clear plastic), high-voltage contacts (copper ring and center wire), and cold plate (bottom of right-hand photograph). Figure courtesy of Jim Fast, Pacific Northwest National Laboratory.

reports a resolution of ~0.4 percent at 662 keV in the latest systems [Can09]. For either mechanically or liquid-cooled systems, the required infrastructure, system size, and system mass pose problems for field use. HPGe has seen limited use as a secondary screening tool for a more detailed evaluation of a suspect item flagged by other systems.

The only room-temperature semiconductor at present is CZT with a typical energy resolution of 1 to 2 percent and a highly linear response (e.g., see [Che08][Fen04][Yon08]). Due to its small crystal size, the absolute collection efficiency required for many applications can be achieved only by integrating crystals into an array (e.g., see [Yon08][Mat06]).

Gaseous Detectors—Proportional and ionization chambers consist of a vessel containing high-purity gas and a readout system, e.g., set of electrodes consisting of a thin central wire. When ionizing radiation passes through the gas volume, atoms or molecules are ionized, and the charge is collected on the electrodes. In proportional chambers, the electric field is sufficiently high that collisions between drifting electrons and neutral gas atoms cause additional ionization near the anode wire; the signal is then proportional to the energy deposited in the gas.

Gases can also be used as scintillators. An incoming photon in a gas, such as high-pressure xenon, will excite xenon atoms to states from which they fluoresce. The xenon detector has sufficient energy resolution (2%) and good proportionality [Kno00]. In principle, xenon detectors could be unlimited in size, but the response slows as the size increases. Significant drawbacks are the packaging and transportation requirements placed on high-pressure gases. In addition, performance is limited by unresolved issues with microphonics and electromagnetic pickup.

The most significant drawback of all gas detectors for ionizing electromagnetic radiation is the low density of the sensitive volume. For example, even in the case of xenon with its relatively high atomic number, its density is ~0.6 g/cm^3 (when pressurized). By contrast, CsI, which has the same probability of interaction on a per-atom basis, has a density of 4.5 g/cm^3—making it about 7 times more efficient per unit volume than a xenon gas chamber.

Photon Detection Systems

Bolometers—Bolometers are unconventional detectors that consist of a superconductor, insulator, and semiconductor cooled to the point that the detecting element's heat capacity is approximately 1 MeV/mK [Net95][Ens05][Irw06]. Absorption of a photon results in an increase of temperature, which results in the creation of phonons. The number of phonons created per deposited unit energy is 2 to 3 orders of magnitude greater than phonons in germanium under the same conditions. The fundamental advantage of cryogenic sensors is ultra-low noise due to low operating temperature (typically 0.1 to 10 K), which can be exploited for extremely high-precision measurement of particle energy, interaction time, or incident power. This translates into ultra-high resolutions [Ull05][Ali08][Dor08], for example 50 eV at 60 keV. **Figure 3** shows the effect of this resolution in the 100-keV range where various lines from uranium and plutonium reside. Multiplexed microcalorimeter gamma-ray detector arrays are now in development and have revealed unprecedented spectral detail of SNM [Dor07].

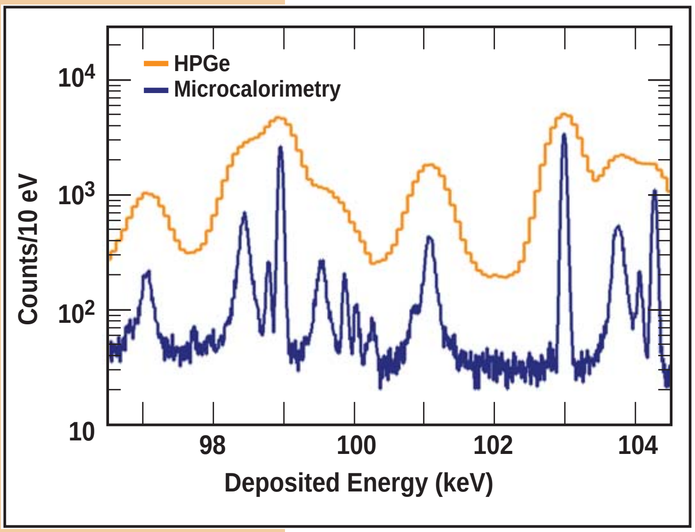

Figure 3. Plot of counts versus deposited energy acquired using microcalorimetry as compared to that of HPGe. This figure demonstrates the separation of various low-energy peaks in Pu not achievable with HPGe. Figure courtesy of Michael Rabin, Los Alamos National Laboratory.

Several key scientific obstacles must be overcome to set the stage for the transition from R&D to development and engineering. To date, this technology has been demonstrated with only a few materials and is limited to approximately 10 events per second. Because the size of the detecting element must be relatively small, the absolute detection efficiency for gamma-ray detection is low. Gamma-ray detector arrays with large format (>100 pixels) have been fabricated and assembled but have not yet shown simultaneous operation of all sensors with high resolution. A combination of improved pixel design and signal processing will be needed to make microcalorimeter speed (event counting rate) comparable to that of HPGe spectrometers while retaining the improved resolution. Improvements in absorber materials will be required to extend the applicable energy range from ~200 keV to several hundred keV; these improvements will also increase per-pixel speed. In-depth understanding will be required to determine both the practical and in-principle limits of uncertainty for quantitative materials analysis (isotopic and elemental ratios) determined from microcalorimeter spectra. For nuclear materials analysis through x- and gamma-ray spectroscopy, microcalorimeter detectors hold the greatest promise for those applications where long measurement times are tolerable and spectral resolution has especially large benefits.

Readout Technology

Photomultiplier Tubes—Photomultiplier tubes (PMTs) convert scintillation photons into electrical signals. The first part of a PMT is a photo-sensitive layer (photocathode) that emits electrons when struck by a photon. The number of electrons is proportional to the photon energy, ideally in a very linear way. The electrons then pass through an amplifying cascade ending with enough charge to be integrated with precision. PMTs offer high gains, large collection areas, and high linearity. The disadvantages of PMTs include temperature sensitivity, high-voltage operation, relative fragility, and relative bulk. While a mature technology, new PMTs have been developed with quantum efficiency up to about 45% at 380 nanometers (nm) [Pan08][Vaq08]. An important factor in the performance of a scintillation system is the spectral overlap between the scintillation wavelength and the sensitivity of the photocathode. The various bialkali photocathodes used in most PMTs have good sensitivity in the ultraviolet and a peak response around 400 nm. The response falls to zero near 600 nm where the photoelectrons no longer have sufficient energy to escape the surface of the photocathode. Most common plastic scintillators have emission wavelengths in the 370 to 580 nm range that are well matched to the photocathode sensitivity. Liquid scintillators have a maximum emission wavelength of 425 nm. Inorganic scintillators span a similar range to plastics (e.g., the peak emission wavelength for NaI is 415 nm), except for some of the fast unactivated inorganics that emit at wavelengths as short as 220 nm.

Photodiodes—Photodiodes also convert scintillation light into electrical signals, but, in contrast to PMTs, photodiodes offer high quantum efficiencies (up to 80% in the infrared, but less in the blue and ultraviolet) in smaller and sturdier configurations with less power consumption. Photodiodes operate on principles similar to PMTs but within semiconducting materials rather than a series of layers and electrodes in a vacuum. Photodiodes have spectral sensitivities that span a much wider range than photocathodes, peaking in the near infrared around 900 nm. The major problem with photodiodes is electronic noise due to capacitance and leakage current, which become worse as the active area becomes larger. Dark current also rises rapidly above room temperature, limiting use at elevated temperatures. This noise can significantly reduce the energy resolution of the detector system. Because of these limitations, PMTs remain the current choice for fielded detection systems. Arrays of avalanche photodiodes, generally called "silicon photomultipliers," are under development that could eventually offer a good alternative to PMTs. Their active areas at the present time are too small to fill such a role in most circumstances.

Semiconductor Charge Collection—Readout technology for semiconductors is simpler in principle than for scintillators, since the induced signal originates in the form of an electrical charge. The most important challenges in charge collection are optimization of the geometry of the material and the electrical contacts that carry the charge from the semiconductor to the pulse-processing circuitry. The use of simple ohmic contacts on opposite faces of a cube of material is seldom an appropriate choice. For example, HPGe detectors are typically fabricated in a coaxial geometry with contacts on the inner and outer surfaces of a hollow cylinder. Semiconductor contacts are often shaped into a variety of rectangles or rings in order to achieve a desired geometry for the internal electric field in the material, which determines the trajectories of the electrons and holes produced in the gamma-ray interaction. For this electric field to efficiently collect charge, an electric potential of O(100–1,000 V) must be applied. Despite this high voltage, it is necessary to minimize the leakage current through the material since the radiation signal will appear as a charge pulse added to the leakage current. When the bulk resistivity of the material is high, leakage current across the surface also must be limited via measures such as surface grooves or guard rings. Semiconductors such as CZT suffer from limited hole lifetime and mobility compared to the lifetime and mobility of the electrons. This results in large tails that emerge on the low-energy sides of full-energy peaks. This has a significant impact on energy resolution. To mitigate this problem, coplanar grids (shown in **Figure 4**), virtual Frisch-grids, and pixilated anodes have been developed to create a system where the majority of signal derives from electron transport [Kno00][Luk95] [McG98][McG99].

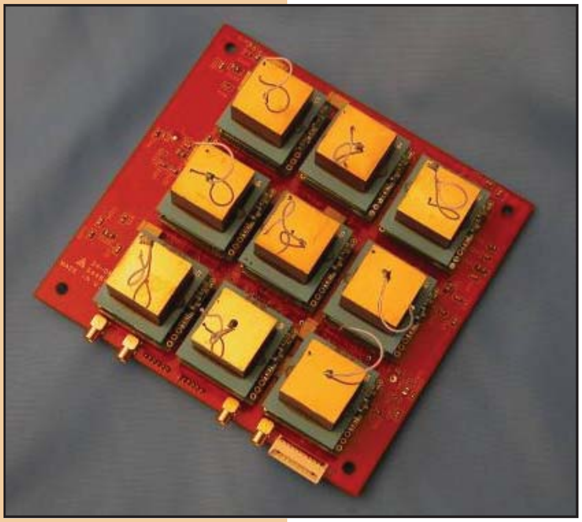

Figure 4. Photograph of nine CZT crystals mounted to a coplanar grid readout (underside of photograph) with cathode wires attached. Figure courtesy of Cari Seifert, Pacific Northwest National Laboratory.

Data Analysis Algorithms

The final step that translates measured events into actionable information relies on data analysis algorithms. In the simplest photon detection systems, an algorithm might consist of a comparison between the counts recorded when a signal is present to a measured background when the signal is absent. More sophisticated analyses make use of a recorded energy spectrum. The vast majority of effort directed at gamma-ray spectroscopy has focused on the problem of unfolding the constituent isotopes in an unknown empirical spectrum.

Peak Fitting—Peak fitting segregates a spectrum into its component peaks and continua. This deconstruction process can be very complex and includes extraction of Compton shoulders and the fitting of Gaussian-shaped peaks with tails. After peak identification, the energies and relative proportions are matched to the known energies of a library of gamma-ray sources. This approach is not overly sensitive to a lack of a priori knowledge of the measurement scenarios. The greatest obstacles here are the difficulties that can be encountered in extracting a particular peak from several overlaid peaks plus background plus other continuum effects. Peak fitting has been successfully applied in codes such as FRAM [Sam97] and MGAU [Ber07], which have been developed for safeguards applications where a specific region of well-populated peaks is under investigation. Peak fitting is also effective in high-resolution spectra, such as from HPGe, that possess a very high ratio of counts in the full-energy peak compared to counts in the continuum.

Template Matching/Basis Vector Fitting—Template matching uses a pre-existing library of radioactive sources and fits them to the measured spectrum. At a minimum, this involves defining a vector of scaling factors applied to the library spectra and a difference minimization routine that adjusts the scaling factors until a best fit to the measured spectrum is achieved. More complexity can be introduced by including scaling factors that adjust the energy axis of the measurement so that gain differences between the pre-existing and measured spectra can be accommodated. Another improvement to this approach is the addition of spectra that incorporate intervening materials. This effectively creates a two-dimensional library of source type and intervening material.

Template matching works very well if the measurement environment is well-defined; e.g., if the pre-existing library is populated with measurements by the exact detector with which unknowns will be measured and with measurements from sources that will constitute the unknowns. As the measurement scenario increasingly differs from the scenarios detailed in the library, the performance of template matching diminishes. The ability to adjust parameters and, in some implementations, make interpolations between different pre-existing spectra increases the robustness of this approach. An example of a developed algorithm is GADRAS DHSIsotopeID, with example results shown in **Figure 5**, which is a high-performance tool when used by a trained analyst.

Time-correlation Analysis—Gamma-ray time-correlation analysis may be used to measure fission gamma rays directly or to measure fission neutrons by detecting gamma-ray emission following neutron capture, but methods are considerably less mature for gamma rays than for neutrons. Neutron-based methods are robust for three reasons that do not apply to gamma ray measurements: (i) neutron backgrounds are low, thus resulting in few accidental coincidences; (ii) fission neutrons readily penetrate metal, thus making valid the assumption of a single detector efficiency connecting the theoretical fission chain to the measured coincidences; (iii) capture-based detectors cannot detect the same neutron twice. Gamma-ray backgrounds from natural activity are much higher than for neutrons, particularly when combined with large solid-angle detectors. One consequence of these higher background rates is that long correlation windows—on the order of milliseconds necessary for measurement of neutron-capture gamma rays—are unlikely to yield statistically significant results in reasonable times for low intrinsic fission rate materials such as HEU. In addition, while the number of fission gamma rays may be much larger than the number of fission neutrons, the number of fission gamma rays that escape from a SNM assembly may be much lower because of self-shielding. Last of all, gamma rays can Compton scatter between two or more detectors, giving a baseline of coincidences proportional to source strength.

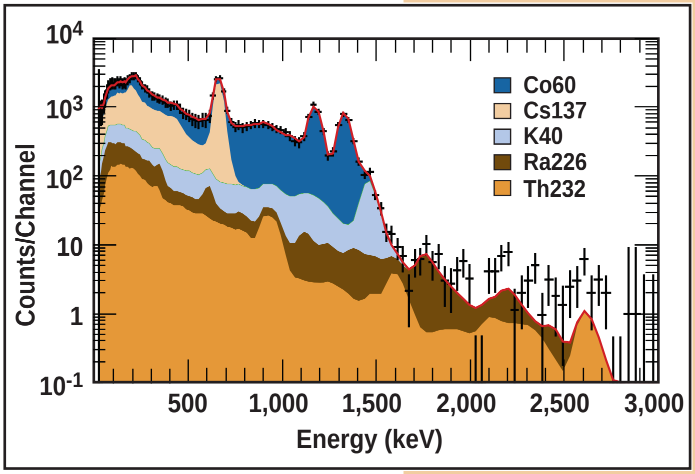

Figure 5. Screen shot of GADRAS DHSIsotopeID results upon analysis of a multi-isotope source. Figure courtesy of Michael Wright, Oak Ridge National Laboratory.

Previous examinations of gamma-ray time correlations focused on the measurement of both gamma rays and neutrons. They have consequently been limited by the detection system's ability to distinguish between gamma-ray and neutron events in detectors that are sensitive to both. Approaches using different detectors for gamma rays and neutrons have struggled to attain adequate absolute collection efficiencies. Because of these measurement challenges, the question remains open as to what value gamma-ray time-correlation measurements add to those exclusively focused on neutrons.

Identification of Shortfalls

In contrast to advanced materials discovery, R&D in photon detection systems addresses limitations that are not intrinsic to the material or to the fundamental detection interaction. Instead, these limitations are imposed by the methods and tools used to collect or interpret detector response data. For a given radiation detection material, the goal is to improve these methods and tools to maximize the collected signal, energy resolution, timing resolution, and deployability while minimizing the cost. At present, there are no radiation detection materials that can be packaged to simultaneously meet all requirements. This roadmap focuses on filling shortfalls associated with the development of high-resolution photon detection systems since high resolution is an omnipresent requirement spanning essentially all applications. A secondary objective is the integration of time-correlation signatures from the photon domain that could potentially complement their neutron counterparts, whose signature exploitation is considerably more mature.

Efficient Readout Technology—Detector systems do not achieve the full resolution available from the detector materials themselves due to limitations in light conversion and charge collection. For example, PMTs do not capture all of the scintillation photons, due to wavelength mismatches between scintillation light and photocathode response, and therefore have reduced sensitivity. In high-count-rate applications, response times of signal collection methods limit sensitivity through the creation of dead time and/or impact resolution through pileup effects. Analogous limitations exist in the collection of charge from semiconductors, most notably in the case of CZT, which requires extensive charge collection schemes to mitigate effects of charge migration and trapping.

Readout technology sometimes fails to meet requirements of compact, robust, low-power systems. For example, absolute collection efficiency may be limited by the physical space required to house PMTs while complex readout electronics consume considerable power and computational resources.

Time resolution shortfalls also exist, particularly in applications exploiting time-correlation signatures or in active interrogation environments.

Automated Gamma-ray Spectroscopy Algorithms—Applications where the rate of photon emission is low require the ability to evaluate sparse data. Other applications may not be limited by the amount of data but by the need to filter out artifacts from the data collection process. Underlying both data processing problems is the presence of background. The rich history in development of gamma-ray spectroscopy tools has focused on analysis performed by trained analysts using medium-resolution detectors. Significant shortfalls reside in the area of automated spectroscopy; this situation is complicated by the minimal computational resources available on battery-operated systems. Even with unlimited computational resources, there exists no completely automated system for reliable isotope identification under a reasonable range of background, shielding, and count-rate scenarios.

Algorithms for Isotope Identification in Active Interrogation Systems—Algorithm development for gamma-ray spectroscopy in active interrogation systems is a largely unexplored area. While prompt emissions from photofission possess a fairly unstructured continuum, delayed signatures from fission daughters possess significant structure. At the other extreme, emissions from nuclear resonance fluorescence are discrete and occur at only a handful of energies. Successful demonstration of active interrogation systems will require the capability to extract these signatures from complex and high-rate backgrounds. In the case of pulsed interrogation systems, algorithms may need not only to examine energy spectra but also include temporal information.

Gamma-ray Time Correlation and Related Signatures—Examination of signatures that arise from timing and multiplicity of gammas could lead to extraction of more actionable information from data that can already be collected by existing hardware. The fundamental shortfall here is the absence of both an accepted estimate of the value of using gamma-ray multiplicity and a proven approach to exploiting gamma-ray multiplicity (with or without neutron correlations). A necessary component to developing algorithms is assembly of a proper quantification of the underlying signature space, especially since questions remain about exactly what additional information gamma-ray multiplicity adds to existing gamma-ray spectroscopy and neutron multiplicity.

Prioritized Investment Options

Detection of gamma rays is ubiquitously applied in SNM detection scenarios. This state will likely persist with the potential deployment of active interrogation systems. Development of photon detection systems is thus a critical high-priority area of R&D, but it is also a mature one with wide applicability beyond SNM detection. The investment options identified by a group of SMEs reflect this reality, and their prioritization by NA-22 addresses the need to target niche areas of photon detector development, including assessment of high-risk approaches that may represent unconventional system development paths. This prioritization scheme, which largely consisted of first ordering options based on their priority in the *SNM Movement Detection Portfolio—Technology Roadmap* and subsequently estimating impact levels, is listed in **Table 3**.

Table 3. Prioritized investment options for photon detection systems.

Investment Option	Priority	Impact	Summary
Alternate radiation detection and readout concepts	High	High	Most of the traditional and non-traditional detector materials discussed earlier rely on scintillation or direct ionization charge collection processes in solids, and much of the research to be done in pursuit of advances in those areas is in the materials science of crystal growth, materials processes, and photon and charge transport. Beyond work on the performance of existing detector materials are novel detection approaches that either use different physical processes or classes of materials not previously developed for SNM detection applications. A high-risk, long-term R&D effort investing in these entirely new approaches might produce revolutionary advances if one of these concepts proves successful. In radiation detection, there exists a handful of intriguing photon-detection methods that have not been explored to a degree that allows a determination of their potential value. Potential avenues of signal extraction include, for example, magnetic properties and response, electromagnetism susceptible devices, and acoustic/piezoelectric properties and response.
Spectroscopy algorithms for signal-starved spectra	High	High	There is a long history in the development of analysis methods for high-count, low-background, low-noise data from high-resolution, and even medium-resolution, detection systems. To fully exploit the potential of spectroscopic systems, further investment is needed to develop new spectroscopy algorithms for signal extraction from noisy and sparse spectra, specifically in automated analysis that does not involve the immediate support of an analyst. No completely automated and reliable system currently exists for isotope identification. One of the largest challenges stems from analysis of spectra with imprecise energy calibrations resulting from gain shifts. Successful development of automated algorithms for fielded systems experiencing gain shifts could provide significant capability advancement.

Table 3. Prioritized investment options for photon detection systems. (cont.)

Investment Option	Priority	Impact	Summary
New strategies for charge collection in semiconductors	High	Medium	In the absence of large-volume, room-temperature semiconductor materials, detector systems will continue to exploit multi-pixel arrays of small-volume crystals. Optimizing the readout of these multi-pixel arrays in a manner that reduces complexity and power consumption is an important near-term objective. Example techniques considered to date include a virtual Frisch grid, pixilation, and co-planar grid readout, but each of these introduces considerable complexity.
Stable, solid-state readout technology for scintillators	High	Medium	PMTs are a well-established commercial technology with considerable ongoing industrial investment, but a viable solid-state replacement with reduced size, increased durability, and the ability to be scaled to large areas does not presently exist. Avalanche photodiodes and solid-state photomultipliers represent two potential solutions. Currently, avalanche photodiodes have limited areas and are unstable with changes in the temperature and bias voltage. Solid-state photomultipliers that count individual scintillation photons have shown promise, but two remaining challenges are increased packing fraction of readout pixels and reduced cross-talk between pixels. Useful implementations of either technology need to have an active area greater than of $O(10\ cm^2)$. Another possible replacement for PMTs is organic semiconductor-based photodiodes. Performance of these materials is currently limited by noise issues and high capacitance for large areas.
Assess deployment feasibility of proven non-traditional radiation detectors	High	Medium	There are several proposed measurement techniques used in fields such as high-energy physics that have evolved to the point where further consideration for application to SNM detection is appropriate. Two examples are cryogenic detection media based on liquid argon and xenon. Liquid xenon offers the potential for a large-volume spectroscopic or tracking detector with good theoretical resolution; liquid argon offers the potential for a large-volume detector with good pulse-shape discrimination between neutrons and gamma rays. Other examples include Cerenkov/transition detectors that have very fast timing and can easily be scaled to large sizes, although they suffer from low light yield and poor energy resolution. Other candidates are bubble chambers for fast neutron detection and gas-filled tracking detectors that may be useful for imaging applications. While well understood in the laboratory, applications development for all of these complex detectors needs to focus on deployment challenges.
Detection limit mapping	High	Medium	In developing detection systems, a balance between sensitivity (the capability to capture signal) and selectivity (the capability to differentiate between signals) dictates what detection media are potential candidates. Detection media with medium resolution that are available in large volumes, e.g., NaI, dominate field deployments because they possess both appreciable sensitivity and selectivity. A comprehensive study of the detection limits as a function of the sensitivity and selectivity parameter space would help guide the development of new detection materials and systems. Of specific interest are crossing points in detection limits between high-resolution but small-volume detectors and medium-resolution but large-volume detectors that directly incorporate energy resolution, linearity, and collection efficiency of existing and emerging detection systems.
Algorithms for active interrogation signatures exploitation	Medium	High	Specifically addressing two of the *SNM Movement Detection Program—Technology Roadmap* priorities is development of algorithms that exploit active interrogation signatures and photon time-correlation data while minimizing the effect of large dynamic range in detector response. An inherent component of algorithm development is the quantification of both the signature and background signal space. A significant contribution to the “background” results from limitations on the dynamic range that may be tested by the high acquisition rates resulting from interrogation sources, for example. Open questions remain regarding how to fully exploit the multiplicity information contained in gamma rays emitted both passively and in response to an interrogating source.

Neutron Detection Systems

Technology Requirements

Since neutron interaction cross sections are modest, especially in the case of fission neutrons, systems must be designed to yield a sufficient number of signal counts in a reasonable time. This requires a combination of scalability to large area and adequate intrinsic detection efficiency. Each of these development objectives were identified as first-priority items in the *SNM Movement Detection Portfolio—Technology Roadmap*. Modest interaction cross sections also lead to two ancillary requirements. First, since gamma rays are omnipresent in large numbers, it is crucial for neutron detectors to be insensitive to gamma rays or to be able to distinguish them from neutrons, at a level of $O(10^{-5})$ or greater when neutron detection is of exclusive interest. This is especially the case for interdiction of SNM where high-activity gamma-ray sources are common in many applications. Second, the large-volume nature of neutron detectors in monitoring applications mandates a low cost per unit volume. Although this may preclude some techniques that can in principle be scaled but in practice have limitations, modern technology can enable complex systems to be fabricated economically.

The vast majority of nonproliferation applications aim to detect the presence of fission neutrons. The common requirement is thus for discrimination between fission neutrons and those at low energies, which dominate background. This implies that the capability of reliably sorting neutrons into low-energy and high-energy categories is highly desirable. For field applications focused on SNM detection, there is limited benefit to neutron spectroscopy over the range of the fission spectrum since empirical backgrounds possess an energy distribution almost identical to the fission spectrum [Gor04]. Applications focused on source characterization can benefit from neutron spectrometry. Two examples include the need to discern a fission spectrum from one produced by an americium-beryllium (AmBe) source and the need to identify the presence of oxide materials—a task that requires high-resolution neutron spectroscopy. The required fidelity of the spectrometer is thus highly application-specific.

Measurements exploiting time-correlation signatures bring additional requirements. The first revolves around the time scale of the fission processes that emits bursts of neutrons with characteristic time scales approximately ranging from 1 ns up to 10 µs. To exploit these correlations, detectors must also possess time-resolving capability at this level. In addition to fast detectors, dual-particle detectors are of interest for time-correlation measurements since emissions very often consist of both gamma rays and neutrons. While current practice relies on separate detectors with separate readouts, future systems must possess the capability to detect both species in the same active detection volume. A further desired feature is the capability to explicitly distinguish between the two types of radiation.

Active-interrogation methods also impose unique requirements. Detectors must function at high event rates to extract the stimulated neutron signal and/or operate during interrogating radiation bursts. Very high gamma-ray discrimination capability may be necessary to distinguish the interrogating radiation from the emitted neutron signal, especially in cases where the induced signal flux is much smaller than the interrogating radiation. Crude neutron energy selectivity, similar to that noted above, may also be necessary to discriminate neutron signals from interrogating radiation. For example, it may prove effective to categorize neutrons as low-energy, fission, and high-energy in the case of interrogation with a 14-MeV generator. For pulsed interrogation scenarios, triggering or gating of the neutron detector may be required.

From the fieldability standpoint, low power consumption, the absence of pressurized gases, and straightforward systems setup are important in some nonproliferation contexts.

Survey of Field

The nature of interaction cross sections inherently bifurcates neutron detection systems into those sensitive to thermal neutrons and those directly sensitive to high-energy neutrons from fission (hereafter referred to as fission neutrons). This section discusses detection methods in this order. Following this is a brief discussion of spectroscopic neutron detectors, which consist of thermal and high-energy detection systems configured in such a manner to extract incident energy.

Thermal Neutron Detectors

Thermal neutrons are most efficiently detected via neutron capture reactions that convert thermal neutrons into high-energy charged particles. Commonly used nuclides include ^{3}He (5,330 b), ^{6}Li (940 b), ^{10}B (3,840 b), and ^{157}Gd (49,000 b) because of their large capture cross sections and the fact that subsequent charged particles are energetic enough to allow discrimination from gamma-ray energy depositions [Kno00]. Detection of fission neutrons using these capture agents requires the positioning of moderating material between source and capture agent. This is generally accomplished using organic polymers or other hydrogen-rich materials with thicknesses of O(1–10 cm).

Gaseous Detectors—Detectors incorporating ^{3}He or BF_3 gas that operate in a proportional-counting mode have seen widespread deployment. Due to the higher cross section, capability of operating at higher pressures, stability with respect to temperature, and environmental and safety concerns, ^{3}He detectors are most common since they have proven to be a robust and reliable detection medium. The technical shortcomings of ^{3}He are the need to operate at high pressure and, being ionization chambers, the response and recovery times of such detectors are limited to microseconds, so that they are suitable for some, but not all, multiplicity measurements. To some degree, subdividing the detector volume into multiple readout channels can increase the overall rate capability without significantly increasing cost or operating complexity. This response time may also limit utility in some active-interrogation methods. Due to their low-Z composition and high-reaction Q values, gaseous detectors have excellent gamma-ray discrimination. At thermal energies, the discrimination power of ^{3}He detectors at $O(10^{-5})$ appears sufficient for most signal-starved applications [Cra91].

Conversion-layer Detectors—The concept of placing neutron-capture agents in intimate contact with a semiconductor or other charge-collecting device is attractive because it obviates the need for high-pressure cells and would be, in principle, both scalable and position sensitive. Various attempts have been made at producing these conversion-layer detectors, but success has been slow in developing.

Two techniques have shown some recent promise. The first relies on coating silicon semiconductors with ^{10}B. To maximize both the ability to capture neutrons and the amount of energy captured from the reaction products, coatings of ^{10}B and ^{6}LiF have been applied to semiconductors with etched holes or trenches [Shu06], as shown in **Figure 6**. Similar concepts use pillar geometries [Nik08]. Neutron detection has been demonstrated using this technique, but overall system size has been restricted to areas of $O(1\ cm^2)$. The affinity of gamma rays for Compton scattering in Si presents a potentially significant discrimination challenge.

Figure 6. Photograph of an array of silicon-based conversion layer detectors, the 6-mm-diameter circles attached to each circuit board. Figure courtesy of Douglas McGregor, Kansas State University.

The straw detector concept applies similar logic, and it may hold more promise for large-area detection since it does not rely on a semiconductor [Lac06]. Straw detector prototypes are being fabricated in 1-m lengths to create a detector panel 1 m^2. The straw concept consists of a $^{10}B_4C$ coating, ~1 μm thick, which is sputtered onto thin ribbons of aluminum. These ribbons are then fashioned into straws that are filled with a gas, creating an ionization chamber. The thermal neutron detection efficiency is reported to be 50%, while the gamma discrimination has been observed to reside at $O(10^{-7})$. The cost and fabrication challenges associated with this technology may be a limiting factor in its deployment.

Materials with Embedded Converters—Embedding neutron capture agents in semiconductors or scintillators provides a more efficient system for collecting the energy released by reaction products, but this technology is immature. One attempt at such an approach tested pyrolytic boron nitride with a natural abundance of ^{10}B at 20 percent [McG08]. These detectors possess reduced mass, exhibit potential for development into 2-dimensional flat-panel arrays, and can be adapted to Si read-out electronics. Fast, gamma-insensitive semiconductor detectors such as SiC are also being developed as fast neutron detectors for active interrogation systems [Rud09]. These detectors can operate in intense radiation fields and have been shown to be capable of neutron-photon discrimination through the use of pulse-shape discrimination techniques.

A great deal of effort has been directed at the development of scintillation-based thermal neutron detectors, primarily for applications in neutron radiography that require high spatial resolution and the capability to operate in large fluxes [Eij04]. Perhaps the most promising of these are Cs_2LiYCl_6:Ce and Cs_2LiYBr_6:Ce, which exhibit neutron-capture pulse-heights well above the terrestrial gamma-ray background ending at ~3 MeV. These materials are presently in the early stages of development and limited to small sizes of $O(1\ cm^3)$ that precludes them from many applications, but significant optimism surrounds these materials, especially due to the potential to provide both gamma-ray spectroscopy and thermal neutron detection.

Neutron Detection Systems

An older scintillator is $ZnS:Ag/^{6}LiF$ which can be painted onto a sheet and read out by wavelength shifting fibers. Recent advances in this approach have led to reports of thermal neutron detection efficiencies of ~40 percent [Koj04], but gamma-ray rejection remains an issue. Recent commercial developments focused on border security have demonstrated success in applying pulse-shape discrimination [IAT09].

Figure 7. Photograph of lithium-doped scintillating fibers. Figure courtesy of Mary Bliss, Pacific Northwest National Laboratory.

Fiber Detectors—Cerium-activated, lithium-silicate glass scintillates upon thermal neutron capture by ^{6}Li (**Figure 7**) [Cra00]. The triton and alpha particles each interact with the glass matrix to produce an ionization trail. This scintillation light at ~400 nm can then by collected by a PMT. The scintillating glass is sensitive to Compton electrons and photoelectrons produced by gamma rays as well as neutrons, but electrons produce much smaller pulses than neutrons. Fiber detectors have achieved some infamy due to the fact that, under exposure to large gamma-ray fluxes, pileup amongst gamma-ray events becomes indistinguishable from neutron events, especially when fibers are fabricated in long lengths. Recent developments in pulse-shape analysis may provide a considerable improvement in the separation between gamma-ray and neutron distributions.

Water Cerenkov Detectors—Construction of high-efficiency, large-volume, and low-cost neutron (and high-energy gamma) detection systems may be possible through the use of water Cerenkov detectors doped with trace quantities of neutron capture agents. This technique relies on the photo-detection of Cerenkov radiation created by gamma-ray emissions from neutron capture agents held in a water solution. This technique has been demonstrated in various experiments, using ^{10}B and ^{157}Gd dopants, in the 250-L prototype shown in **Figure 8** [Daz08]. The use of ^{157}Gd (in natural Gd) is promising because its 8-MeV cascade of gamma-ray emissions provides sufficient Cerenkov radiation to be detectable even with modest (10%) PMT coverage.

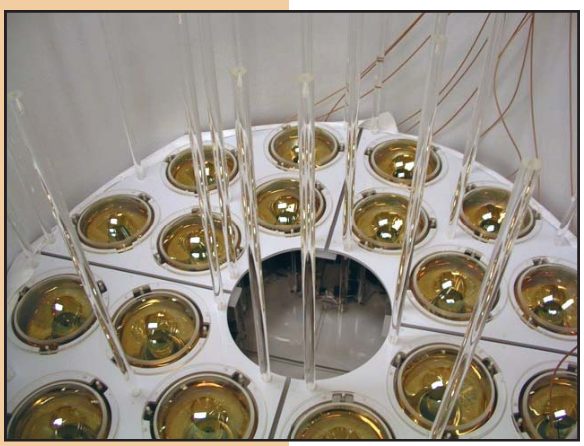

Figure 8. Photograph of prototype water Cerenkov neutron detector. Figure courtesy of Steve Dazeley, Lawrence Livermore National Laboratory.

Direct Fission Neutron Detectors

Methods to detect fission neutrons generally rely on elastic scattering between neutrons and hydrogen. The amount of absorbed energy is a crucial parameter for signal extraction and differentiation from gamma-ray depositions. While any nucleus could, in principle, function as a recoil detector, the amount of energy a target nucleon can absorb quickly decreases with increasing atomic number. Fast neutron detection systems have thus almost exclusively relied on hydrogen-rich (organic) compounds.

Organic Scintillators—Plastic or liquid organic scintillation detectors are common tools used when counting of high-energy neutrons is the goal. Organic scintillators possess advantages in terms of low cost and fabrication into large sizes. Since they are both neutron detection and moderation media, layers of these detectors can be used to measure crude neutron energy distributions, in a similar manner to gaseous detectors inside moderators (discussed below). With their excellent response and recovery time of O(0.1–1 ns), they are useful for fission neutron multiplicity counting. When doped with neutron capture agents, they can be made sensitive to thermal neutrons as well [Swi08].

Organic scintillators are sensitive to gamma rays, particularly via Compton scattering. This presents the possibility of dual gamma-ray/neutron counting at relatively low cost but also requires the development of gamma-neutron discrimination techniques. Pulse-shape discrimination is fairly mature and successful in liquid scintillators but is a strong function of energy (see [You09] and references therein). Fieldability is a prominent issue since some liquid scintillators are toxic and flammable. Their light output can be affected by temperature variations at the level of a percent per degree Celsius, but mitigation techniques are quite practical.

Plastic scintillators have seen much wider deployment, but normally as gamma-ray detectors due to the inability to perform pulse-shape discrimination. One exception is stilbene, which is a unique (and expensive) solid organic scintillator. Stilbene has excellent pulse-shape discrimination capabilities [Esp04] but is problematic due to its high cost and a manufacturing process that involves the use of toxic and carcinogenic materials. Recent advances in alternate materials have shown promise, for example in the case of triphenylbenzene, whose pulse-shape discrimination relative to stilbene is shown in **Figure 9**. Attempts have been made at gamma-neutron discrimination in traditional plastic scintillators based on the delay between multiple neutron scatter events instead of pulse-shape discrimination [Ree99], but no recent results have been reported.

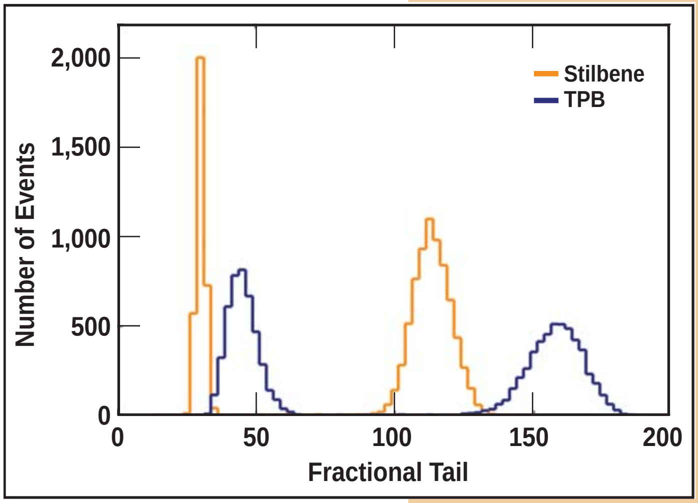

Figure 9. Plot comparing neutron-gamma discrimination for stilbene and tetraphenylbutadiene. Data courtesy of Natalia Zaitseva, Lawrence Livermore National Laboratory.

Time Projection Chambers (TPCs)—Light gas-based (H or He) TPCs have been used for many years in the high-energy and particle physics communities to detect and characterize products of exotic, high-energy particle reactions. The principle of operation of TPCs is discussed further in the *Imaging Methods* section. There are ongoing efforts to convert these large and complex detectors into fieldable detection systems for nuclear search and monitoring applications [Hef09], as shown in **Figure 10**. The benefit of this approach is scalability to large detection volumes, nearly 4π field-of-view, high-efficiency (10% or better), and the ability to deduce directionality from a limited number of neutron events, as discussed in the *Imaging Methods* section. The major challenge here is the development of a pressure cell that is both practical and safe. Ruggedized and reliable electronics, which also simplify operation and provide largely automated operation, can be implemented.

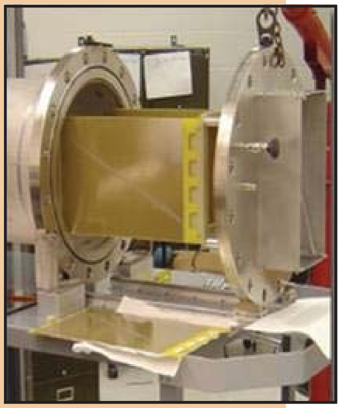

Figure 10. Photograph of prototype TPC including the aluminum pressure vessel and wire grid for charge collection. Figure courtesy of Mike Heffner, Lawrence Livermore National Laboratory.

Chemical Vapor Deposition (CVD) Diamond—A fission neutron detection technique distinct from those above exploits the $^{12}C(n,\alpha)^9Be$ reaction. One prototype detector consists of thin CVD diamond films of O(100 μm) mounted onto a conductive layer of boron-doped CVD as a backing contact [Alm08]. Silver electrodes are then attached to this conductive layer. Positive observations of peaks associated with the $^{12}C(n,\alpha)^9Be$ reaction along with $^{12}C(n,n')3\alpha$ scattering have been reported. The efficiency of such a detector is a major challenge because of the low cross section for the $^{12}C(n,\alpha)^9Be$ reaction and the cost associated with CVD diamond fabrication.

Threshold Detectors—Threshold detectors exploit neutron interactions that occur only above specific energies and thereby provide direct sensitivity to fission neutrons, along with intrinsic insensitivity to gamma rays and low-energy neutrons. One example is the pressurized-liquid bubble chamber, shown in **Figure 11**, which detects neutrons via nucleation [Jor05]. Detection systems based on threshold-detection methods reside in an immature state due to challenges associated with pulse-mode operation, event readout, and/or low duty cycles.

Neutron Spectroscopy

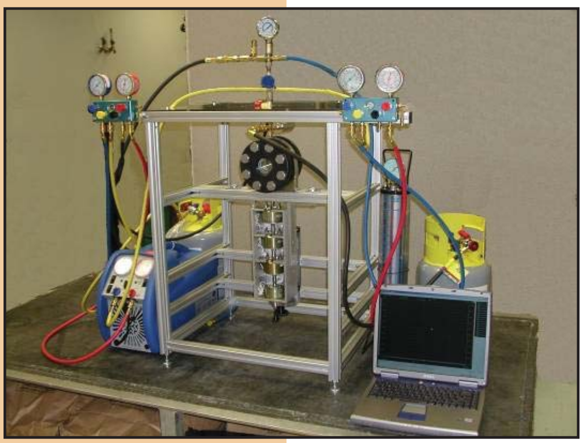

Figure 11. Photograph of a pressurized bubble chamber assembly. Figure courtesy of David Jordan, Pacific Northwest National Laboratory.

There exist several methods to determine the distribution of an incident neutron energy spectrum. They are presented here roughly in order of increasing spectral resolution.

Bonner Spheres—While more frequently used as counters, it is possible to extract spectroscopic information from gaseous proportional detectors. The method is based on deconvolution of signals from multiple “Bonner spheres” that consist of thermal neutron detectors surrounded by varying thickness of moderators [Gol02][Aro97]. This technique requires careful modeling of the detection system and application of complex unfolding algorithms that incorporate response functions, efficiencies, and geometrical dependences. Such spectroscopic systems are in some respects operationally simple, since the neutron energy is selected according to the thickness of the moderating material, but cumbersome due to their extensive size. The principal drawbacks toward their application to nonproliferation are extended measurement times and the need for extensive modeling and simulation to support deconvolution.

Time of Flight—The velocity, and thus the energy, of a neutron can be deduced by measuring the time of flight between two scattering events. Estimates of neutron energies are an integral part of the neutron scatter camera discussed in the *Imaging Methods* section. The time-of-flight technique has been used in nuclear physics experiments for some time, but the development of a recent transportable system has allowed for higher-fidelity environmental measurements, such as the ambient neutron spectrum shown in **Figure 12** [Mas08].

Bolometry—Present research is investigating the use of superconducting transition edge detectors for neutron spectroscopy [Nie04]. These devices operate on exactly the same principle as described in the *Photon Detection Systems* section, but they use materials with large neutron-scattering cross sections, e.g., $Ti^{10}B_2$ and ^6LiF. Energy resolution with a 50-keV full-width half-maximum has been demonstrated for thermal neutron capture [Hau06]. The use of ^6Li allows for fast-neutron spectroscopy, but the cross section for capture above thermal energies is small. These devices have very high resolution but are limited in size and hence overall efficiency by the heat-conducting properties of the neutron-absorbing elements they contain. Attempts to circumvent this shortfall by multiplexing large arrays of such sensors are now being pursued [Hor07].

Nuclear Recoil—In liquid scintillators that have pulse-shape discrimination capability, limited spectroscopy can be performed on neutron events down to the ~0.5-MeV threshold for reliable pulse-shape discrimination. Although the recoil spectrum is approximately flat for monoenergetic neutrons, spectroscopy may be accomplished by unfolding the induced recoil spectrum from the detector response. Zimbal et al. discuss this process in standard NE213 liquid scintillator, demonstrating 11% resolution for monoenergetic 2.5-MeV neutrons (see [Zim04] and references therein). This approach is greatly complicated by shielding and neutron scattering, but further analysis of reconstruction methods in liquid scintillator may provide additional characterization capability for SNM.

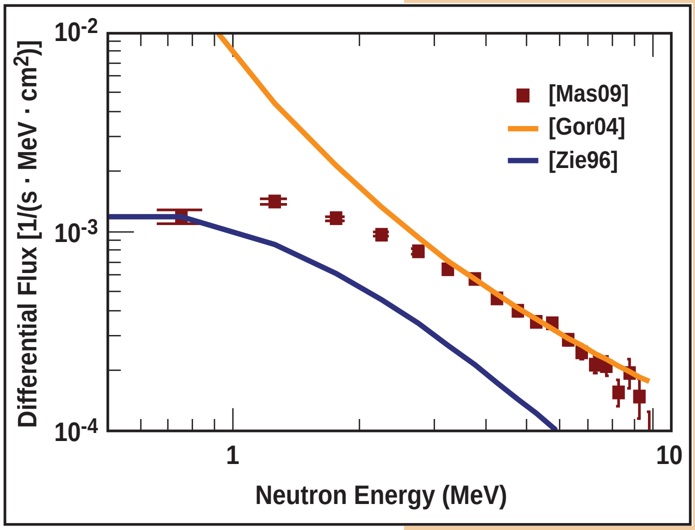

Figure 12. Empirical energy spectrum of ambient neutron background as measured by the neutron scatter camera. Data courtesy of Nick Mascarenhas, Sandia National Laboratories.

Identification of Shortfalls

Neutron detection systems play a crucial role in nonproliferation, especially in scenarios with significant attenuators, because of their ability to penetrate many materials. In spite of this fact, deployments of neutron detection systems almost universally consist of gaseous ^3He proportional counters. While the capability of advanced systems, such as those based on liquid scintillators that directly detect fast neutrons with fast timing, has been clearly demonstrated, present shortcomings prevent the widespread deployment of these capabilities. Deployable technologies must be developed before the high-level objectives of detecting shielded material can be achieved, if complex signatures such as neutron and gamma-ray time correlations are to be exploited.

High Gamma-ray Rejection in Real-time Detectors—The single largest impediment to deploying next-generation neutron detectors is the need for high gamma-ray discrimination. This shortfall exists in both the detection of thermal and fission neutrons. For fission neutrons, state-of-the-art discrimination capability is of $O(10^{-3})$ using liquid scintillator detectors. Further research is necessary to improve discrimination in this energy regime to rejection powers of at least $O(10^{-5})$. These improvements are especially needed for detectors deployed in active-interrogation environments. Additionally, the particle identification capability of fast neutron detectors is energy dependent, and, for them to be versatile, the energy threshold at which discrimination can be achieved must be lowered.

While neutrons from fissile material are produced with typical energies around 1 MeV, interactions with shielding materials or surroundings often reduce the neutron energy to the 10-keV scale. In this regime several things occur: thermal neutron detectors are insensitive; conventional pulse-shape discrimination techniques in scintillators fail; and gamma-ray backgrounds increase compared to the MeV scale. As such, the ~10–500-keV neutron energy region is a “blind spot” in current radiation detectors for nonproliferation. In this regime, radiation detectors lack either efficiency, particle identification, or both. In specific applications, for example those with neutron sources emitting discrete energies, detection systems with particle discrimination down to the 10–100-keV level could improve SNM detection capabilities.

Performance of fiber-based systems is considerably worse, and development of improved detection materials and/or pulse-shape discrimination is necessary. Some threshold neutron detectors, such as bubble chambers, possess excellent discrimination, but real-time detection has yet to be accomplished in an automated fashion.

Replacement for ^{3}He Proportional Counters—Increased demand and vanishing supply of ^{3}He has resulted in significant cost increases for ^{3}He-based systems. With the expectation that ^{3}He will not be available in the coming years, development of replacement systems is a high priority. Next-generation systems need to maintain efficiency and scalability to large area. Ideally, future systems would be directional fast neutron detectors.

Time-correlated Signatures and Observables—The *SNM Movement Detection Portfolio—Technology Roadmap* assigns first priority to the exploitation of time-correlated signatures as a means to detect shielded SNM. Further improvement in the understanding of the joint probability distributions on the number, energy, time scales, and angle of both neutron and gamma-ray emissions may enhance the exploitation of time-correlation signatures and allow for maximally selective detection systems. Simulation capabilities are required to understand these correlated emissions, especially from complicated source geometries possessing multiplication. The development of algorithms to discriminate these emissions from cosmic-induced backgrounds, which also need further quantification, is a present shortfall that must be addressed in parallel with systems development.

Neutron Spectroscopy—There is at present no robust, practical method of performing neutron spectroscopy in situ. Thermal neutron detectors with variable moderators require extended measurement times, physically large systems, and challenging deconvolution algorithms. The emerging technique of microcalorimetry possesses high resolution but minimal detection efficiency. Recoil-based detectors possess reasonable efficiency and can be assembled to cover large areas. In these detectors, resolution on monoenergetic sources can be as good as 11% at 2.5 MeV [Zim04], but, as with thermal systems, spectral deconvolution is a challenge. To date, the method that has come closest to meeting deployment needs are time-of-flight systems, but these systems suffer from a cumbersome geometry, the requirement of two well-separated detector planes, and high-fidelity time resolution.

Prioritized Investment Options

Development of improved neutron detection capabilities is an active field of endeavor. While many potential R&D avenues exist, the following options are those identified by a group of SMEs and prioritized by NA-22 to best meet the broad range of requirements and fill shortfalls. This prioritization scheme, which largely consisted of first ordering options based on their priority in the *SNM Movement Detection Portfolio—Technology Roadmap* and then by estimated impact levels, is listed in **Table 4**.

Table 4. Prioritized investment options for neutron detection systems.

Investment Option	Priority	Impact	Summary
Large-area, thermal neutron detection systems	High	High	Replacements for ^{3}He proportional tubes would have broad applicability to almost all SNM detection scenarios. Scalability at reasonable cost and complexity is essential. Gamma-ray rejection may not need to match the performance of ^{3}He initially, but it must in principle have the potential to do so. In addition to traditional applications, these detectors are of interest for time-correlation studies, but to be useful here they must possess segmentation and μs-scale timing.
Large-area, fission neutron detection systems	High	High	Considerable advancement of detection capabilities would occur if neutron detection systems could be developed that are insensitive to low-energy backgrounds and can be scaled into large-area systems. These detectors must be robust, fieldable, non-toxic, non-flammable, and preferably capable of resolving multiplicity for time correlation. The capability to operate in active environments is desirable but not required. These objectives create the need for high gamma-ray discrimination and reasonable power consumption. The potential of threshold detectors toward meeting these goals should be considered, but a clear path toward overcoming present development challenges must be addressed. Coherent system design is crucial and prototype systems are essential in the R&D phase to identify potential capabilities.
Algorithm development for exploitation of time-correlation observables	High	Medium	The existence and partial character of time-correlation signatures have been documented, but the value of fully exploiting such signatures for nonproliferation has not been firmly established. This is partially due to the need for more precise quantification of signature properties on both the theoretical and empirical fronts. The ultimate goal of quantifying the benefits of time-correlation observables in specific applications requires the development of signal-extraction algorithms and of particular interest here is the development of algorithms that effectively discriminate SNM fission observables from those of ambient background and cosmic-ray events.
Measurements and phenomenological modeling of SNM fission signatures	High	Medium	Proper exploitation of time-correlated signatures requires a thorough understanding of the joint probability distributions of the energy, number, angle and arrival time of neutrons and gamma rays emitted by the various isotopes of interest. Time-correlated signatures arise not only from spontaneous fission but also after induced fission. For both passive and active cases, collection and analysis of nuclear data will allow more sophisticated detection algorithms to be developed and influence detector development. Signature knowledge is especially important for shielded HEU detection, and exploiting such knowledge requires faster and higher-fidelity simulation tools.

Table 4. Prioritized investment options for neutron detection systems. (cont.)

Investment Option	Priority	Impact	Summary
Measurements and phenomenological modeling of cosmic-ray induced neutron backgrounds	High	Medium	The structure in energy, time, and spatial distributions of cosmic rays is an important and poorly understood background for SNM detection using neutrons. This is particularly true for low-signal applications, such as nuclear search and portal monitoring but may also be relevant for characterization and verification applications where rates are generally higher. A thorough understanding of the joint probability distributions of the energy, number, angle, and arrival time of neutrons and gamma rays emitted by cosmic events is needed.
Solid-state thermal neutron detection systems	Medium	High	Robust replacement detectors for ^{3}He proportional counters are needed for small-scale systems, such as handheld and human-carried units. Solid-state detection systems, which may not be scalable to large sizes at a reasonable cost, are particularly desirable. Such detectors must possess comparable intrinsic efficiency to ^{3}He and would preferably operate at lower bias voltages and consume less power. Excellent gamma-ray discrimination would considerably increase deployment capabilities. Fast timing at the μs scale is not required. Semiconductor-based detectors may be particularly good candidates with those based on embedded neutron absorbers possessing considerably more promise than those based on converter layers due to the requirement of high intrinsic efficiency.

Imaging Methods

Technology Requirements

Gamma-ray imaging continues to be a robust field of R&D despite its inception over 50 years ago, particularly in medical imaging and astrophysics. Although developments from other fields, most notably astrophysics, have catalyzed the development of gamma-ray imagers for SNM detection, SNM detection presents unique problems that have not been adequately addressed. For instance, the use of gamma-ray imagers for SNM detection often involves detection of higher-energy gamma rays (up to 3,000 keV) than in medical imaging applications ($\leq$ 100 keV).

Applications in need of location technologies range from directed search, where a source potentially resides in a bounded region, to safeguards and verification, where it is necessary to understand the distribution and quantity of SNM. While this broad application space presents a wide range of requirements, imaging systems have not seen widespread deployment because of their inability to suitably trade off two key parameters: angular resolution and detection efficiency.

Angular resolution is the figure of merit that distinguishes imaging systems from conventional detection systems. In some applications, the necessary resolution is a function of the measurement geometry but could be of $O(1\text{–}10°)$. These rather stringent requirements stem from cases where one actually desires to attain an image of the environs, such as in the case of warhead dismantlement verification. Another application class uses angular resolution to discriminate against ambient background, in addition to gamma-ray spectroscopy for example. Here, the added value of imaging systems is their ability to analyze emissions in terms of intensity and spectral character from different regions of space, which may be as coarse as distinguishing between forward and rear fields of view. Irrespective of whether an actual “image” is reconstructed, imaging systems have the ability to encode spatial information from detected events, and this information substantially improves the signal-to-noise ratio in many applications [Zio02b] [Wur06].

Spatial information is of great value, especially in applications involving large standoff distances, but it is not a singular requirement. Detection efficiency is an essential requirement that plays just as critical a role in the development of imaging systems as it does in the case of spectroscopy. In spectroscopy, mid-resolution scintillators dominate system deployments because of the capability to fabricate large-area detectors. An analogous paradigm will likely govern deployment of imaging systems: a balance must be found between imaging efficiency (the fraction of events interacting in the detector that can be reconstructed) and angular resolution. The key figure of merit in imager development is thus the ability to attain spatial information without sacrificing more than a commensurate amount of detection efficiency.

When considering deployment of an imaging system in a specific application, the signatures of interest must be understood. Consider the case of gamma-ray detection, where some applications require detection systems be efficient across a broad range of energies from 50 to 3,000 keV. These present considerable challenges to imaging systems whose operating principles may possess the necessary sensitivity only in specific energy ranges. Other applications may focus on discrete lines of interest, such as a hold-up measurement of the 186-keV line from ^{235}U. When pondering the development of imaging systems for applications, it is crucial to understand the interplay between signatures and the energy dependence of both the angular resolution and detection efficiency, especially in the case of gamma rays.

Now that an array of imaging systems have been tested and evaluated in laboratory settings, a major requirement for development of next-generation systems is deployability. Imaging systems must be converted into automated systems not reliant on exhaustive data processing and analyst interpretation. Overall system sizes must be manageable and allow mobility.

Survey of Field

This section surveys a range of methods, technologies, and design concepts for gamma-ray and neutron imaging systems. Gamma-ray imaging methods are enumerated first, because these methods are generally more advanced, and many of the neutron imaging methods derive from their gamma-ray brethren.

Gamma-ray Imaging Systems

Occluded Arrays—The occluded array is not an imaging system in the purest sense, since it does not produce an image, but systems based on this concept provide directionality and are a potentially powerful method of detecting SNM. The simplest form of an occluded array consists of one or more detectors surrounded by one or more collimators (e.g., see [Ste05] [Mer07]). Using this simple approach of suppressing the background with a collimator, it may be possible to improve system performance, especially in search applications. Because of the high energy of gamma rays, collimators require considerable mass and volume to effectively shield detectors, and this precludes their use in some applications.

A variation of the simple collimator is an array of detectors that shield themselves, as shown in **Figure 13**. (Similarly, a monolithic detector, in which the locations of gamma-ray interactions can be determined, would serve the same purpose (e.g., see [Kay07]). There are two different ways that a self-shadowing array might be operated. The simplest method is to infer source direction from the difference in the total counts recorded in each detector. Another approach relies on timing methods to note near-coincidence events between detectors. The coincidences are then rejected, which enhances the differential counts. Alternatively, the coincident events provide a simple Compton scatter modality. The lack of a collimator makes this concept more efficient per unit mass, but scenarios arise in which the attenuation of a detector is not sufficient, and collimators are a more effective choice.

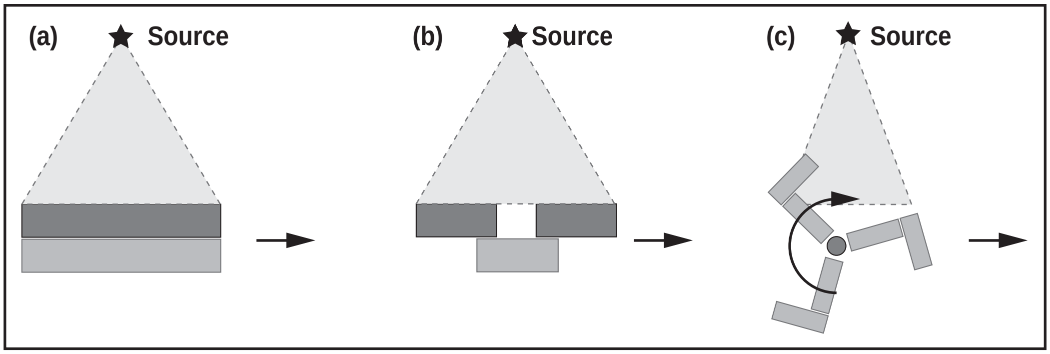

Figure 13. Simple detector configurations provide rudimentary directionality information without using a collimator. The configuration in (a) allows the determination of source direction by the difference in count rate between two detectors. In (b), detectors in the top layer act as attenuating elements as well as detectors. In (c), a rotating collimator with a single detector at the center produces directional information. Figure courtesy of Kai Vetter, Lawrence Berkeley National Laboratory.

Spatial Modulation—There are considerably more sophisticated methods of using collimators that provide spatial modulation. The simplest example of a modulator—and one particularly relevant to radiation imaging—is a pinhole camera that consists of a position-sensitive detector placed behind a pinhole aperture in direct analogy to production of optical images. With exquisite performance in terms of angular resolution, such a system possesses minimal detection efficiency.

More sophisticated versions of the pinhole camera consist of masks that impart a shadow onto position-sensitive detectors by attenuating the gamma-ray flux [Fen78]. The logic here is that if a pattern of pinholes are used, and the pattern can be completely deconvolved from the image, one will attain essentially the same angular resolution and contrast as a pinhole camera but with increased efficiency. The development of these coded-aperture instruments was largely driven by x-ray and gamma-ray astronomy. Coded apertures are well-suited to the problem of imaging distant point like objects in settings with modest background. In contrast, coded apertures were less successful in medical imaging where the object is in the near field, large in extent, and often situated in a highly diffuse background. Development of imaging systems for detecting gamma rays from SNM resides in a space between these two cases: point sources are often of interest, but they are located in a diffuse background.

Coded apertures capable of imaging SNM have been successfully developed and demonstrated. **Figure 14** shows an example coded-aperture imaging system [Zio02]. One important technical challenge in developing imagers is the design of an attenuator that operates efficiently across the gamma-ray energy spectrum. Attenuation of low-energy emissions in the 100-keV range may be achieved with a reasonable mask thickness. As the energy increases to the MeV range, coded apertures necessarily become massive [Zio04].

Compton Scattering—Compton cameras are popular for imaging applications with energies in excess of ~500 keV where the Compton scattering cross section is dominant. Compton cameras were invented by gamma-ray astronomers for use in balloon-borne

Imaging Methods

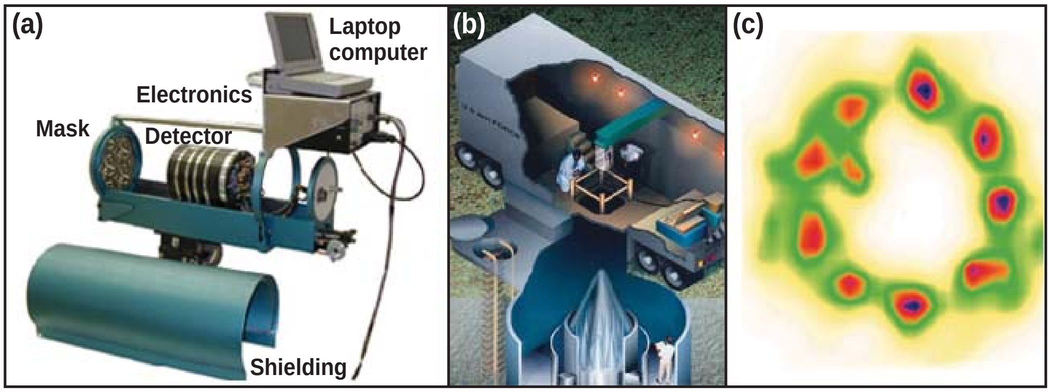

Figure 14. The Gamma-Ray Imaging System (GRIS) is a coded-aperture system developed for treaty verification purposes [Zio02]. It consists of a NaI scintillator viewed by a position-sensitive photomultiplier modulated by a tungsten mask. Pane (a) shows a photograph of the instrument with the light and gamma-ray shield removed. Pane (b) depicts the concept of operation. Pane (c) shows a reconstructed image of gamma-rays from a MIRV'ed ICBM taken with the instrument; the number of warheads (10) can be discerned from the image. Figure courtesy of Klaus Ziock, Oak Ridge National Laboratory.

or satellite-deployed gamma-ray observatories. These cameras rely on inverting the kinematics of Compton scattering. By measuring the energy of the scattered electron and the scattered photon along with their locations, it is possible to reconstruct one of the angles of incidence of the gamma ray. In determining one angle of incidence, the source's position can be limited to a conical surface—as opposed to a line in a perfect imaging system. One method of reconstruction then relies on back-projecting cones from multiple events. The artifacts produced by back-projection are substantial in a Compton camera and dramatically reduce the contrast in the reconstructed image. Higher-resolution images are possible with iterative reconstruction methods (such as maximum likelihood estimation) at the cost of increased computing resources.

Scatter cameras often consist of two detection planes: the front plane measures the position and energy of the scattered electron, a.k.a. the scatter plane, while the rear plane measures the position and energy of the scattered photon, a.k.a. the absorber. In the scatter plane, one is only interested in Compton scattering events; there is thus a disadvantage in increasing figures of merit familiar to spectrometers, such as the atomic number (and consequently photoelectric absorption). Some incarnations of Compton cameras thus employ two different materials: a low-Z material in the scatter plane and a high-Z semiconductor for the absorber. While there are several design parameters that determine the angular resolution of a scatter camera (e.g., see [Phi95]), the angular resolution is in practice dominated by the energy resolution of its detector elements. A variation on this theme that does not rely on the presence of an absorber layer consists of multiple layers of low-Z scattering planes that foster multiple scattering events (e.g., see [Row06]).

In terms of angular resolution, the highest performance Compton cameras incorporate semiconductor arrays because they offer superior energy resolution. Compton cameras based on semiconductors were first constructed from germanium but later from silicon-germanium hybrids, where the low-Z silicon is located in the scatter plane and germanium is the absorber [Vet04]. Although the first semiconductor Compton cameras were constructed from arrays of discrete detector elements, it became apparent early in the development of this technology that the use of monolithic detectors is advantageous. One design entails the use of a two-sided strip detector, such as the one shown in **Figure 15**.

There has also been a great deal of effort directed at development of CZT imaging systems. These include Compton cameras developed from discrete detectors [Ded07] and those developed from monolithic systems [Leh04] [Xu06]. The latter do not rely on discrete scattering and absorption detectors but instead on the reconstruction of scattering and absorption positions within a single element using depth-sensing techniques. This depth-sensing approach offers a compact design alternative which might be ideal for applications that do not require large absolute collection efficiencies since crystal sizes are presently restricted to $O(1\ \text{cm}^3)$. Recent developments of CZT imaging systems consist of arrays of discrete detector elements whose events are combined to essentially create a larger monolithic element [Myj08].

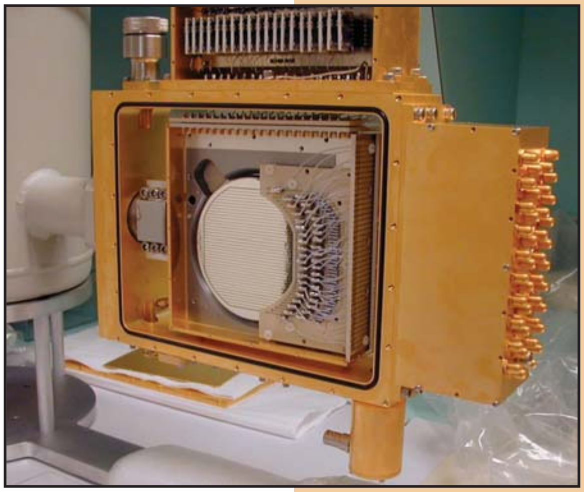

Figure 15. Photograph of a germanium double-sided strip detector [Vet06]. This particular detector has 38 strips on each side and thus contains 1,444 effective pixels, yet is read out into only 76 channels. This particular detector has an active area of about 50 cm^2 and is 11-mm thick. Figure courtesy of Kai Vetter, Lawrence Berkeley National Laboratory.

Recoil Particle Tracking—Reconstruction of a three-dimensional track from Compton-scattered electrons creates the potential for more precise event reconstruction. For example, contemporary Compton cameras reconstruct one of the two incident angles of a detected gamma ray. If the trajectory of the scattered electron could be determined in the scattering detector, then both incident angles of the gamma-ray interaction could be reconstructed, which would result in a set of pointing vectors as opposed to overlapping cones.

One method of employing such electron-track-based reconstruction techniques involves pressurized time projection chambers (TPCs) because of their capability for three-dimensional track reconstruction of electrons. Ueno et al. recently demonstrated the feasibility of a Compton camera using a TPC as the scatter detector and an array of scintillators as the absorption detector [Uen07]. An alternate mode of operation in these detectors involves reconstructing the electron track alone, in analogy to neutron TPCs. Such a method would yield reduced, but potentially sufficient, angular resolution. On the semiconductor front, investigation of the possibility of tracking the direction of the scattered electron in silicon is under way using a variant of the silicon drift detector [Cas06][Cas07]. Yet another method for electron tracking in the scatter plane entails using crossed scintillating fibers to reconstruct the electron track [Bol98], but no recent results have been reported.

TPCs may prove difficult to apply to gamma-ray detection because of their limited stopping power and, in some high-rate applications, possible dead-time limitations. The prodigious data production from a gamma-ray TPC would be a challenge to process and reconstruct with limited computational power. Though such reconstruction is routinely performed in high-energy physics experiments, the computing cost per channel would have to be adapted to the relatively small unit costs that are relevant for field-deployable devices

Hybrid Modulator Scatter Camera—Because modulator-based systems are most practical at low gamma-ray energies and scatter-based systems are advantageous at higher energies, hybrid systems that use both modulation and scatter elements have been developed to operate over a wide energy range. A novel variant of the hybrid approach uses a combined "active coding aperture" and Compton camera. In this approach, aperture elements are themselves detectors that serve as modulators in the coded-aperture mode of operation and as a scattering plane in Compton-scattering mode. Theoretically, the active mask approach could also offer increased effective mask opacity over passive mask elements by actively vetoing low-angle scatter events that would otherwise pass through the coding mask and interact with the imaging plane. Recent studies indicate that the active mask approach may not in practice increase opacity substantially at higher energies [Cun07], but such an instrument might offer substantial performance increases in terms of performance per unit instrument mass (compared to hybrid approach with a passive collimator), since most of the mass of the instrument would be comprised of active detector elements.

Neutron Imaging Systems

Spatial Modulation—Imaging of thermal neutrons has relied exclusively on spatial modulation schemes. While it is in principle possible to modulate high-energy neutrons, the relative transparency of materials at high neutron energies has deterred such development. Effective passive masks for high-energy neutron modulators would have to be very thick of O(10 cm), and, if respectable angular resolution were required, masks would have to be of O(1 m) in size. These thickness requirements may be reduced by the use of active masking elements, but it is not clear by how much.

Scatter Cameras—Neutron scatter cameras operate on a principle similar to Compton cameras: they deduce directionality from two discrete events in two detector planes. The crucial design difference arises from the fact that neutrons have a rest mass that allows their energy to be deduced from their velocity. Instead of the second detector plane acting as a calorimeter to measure the scattered neutron's total energy, its energy can thus be measured via time of flight between the first and second scatter planes. This is an essential element of a neutron imager, since effective neutron spectrometers do not yet exist. **Figure 16** illustrates this process.

If the energy of the scattered neutron is not excessive and the distance between scattering planes is not too small (equal or greater than tens of centimeters), time-of-flight energy deduction can be accomplished with modern PMTs and readout electronics. But because neutron scatter cameras rely on elastic scattering of neutrons, the pool of candidate detector materials is effectively limited to organic scintillators. Because they are well understood, readily available, inexpensive, and capable of pulse-shape discrimination, liquid scintillators have been the detector material of choice for neutron scatter cameras to date [Mas08]. Although it is possible to reject gamma-ray events in a plastic-scintillator-based scatter camera using time of flight between detector elements, and this approach has been used with some success [Van07], time-of-flight alone cannot provide the discrimination required to operate in high-gamma backgrounds due to naturally occurring radioactive material.

Other candidate materials for neutron scatter cameras are the organic crystals anthracene, *trans*-stilbene, and their relatives. Unlike plastic scintillators, organic crystals are capable of effective gamma-ray rejection through pulse-shape discrimination, but these organic crystals are not readily available, have only been fabricated in small sizes, and are relatively expensive. Researchers have reported an anisotropy in the response of these crystals depending on the direction of neutron scatter from the crystal [Bro74]. If observations of the decay characteristics of the scintillation pulse could correct the anisotropy, then it is possible that organic crystals could become candidates for use in high-energy neutron imagers. Size, cost, and availability issues must be resolved for these to be competitive with organic liquid or plastic scintillators.

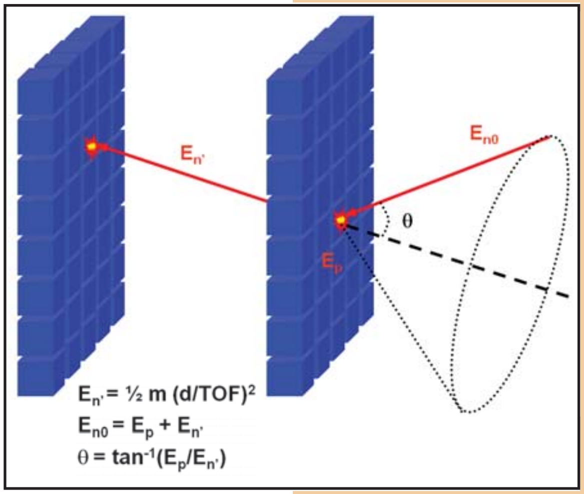

Figure 16. Diagrammatic representation of neutron scatter camera operation. E_{n0} refers to the energy of the incoming neutron, and $E_{n'}$ the energy of the neutron scattered from the front detector plane to the rear. Figure courtesy of Nick Mascarenhas, Sandia National Laboratories.

The energy range over which neutron scatter cameras can effectively operate is determined largely by the operating range of the detector elements. For typical scintillator elements, this range is $\gtrsim$ 100 keV. If unscattered fission neutrons are of exclusive interest, then this threshold is acceptable. If one desires to detect downscattered neutrons, then a lower threshold may be desirable.

Recoil Particle Tracking—It is possible to perform neutron imaging by using the double scatter of non-relativistic neutrons off of ambient protons by tracking the recoil protons. This technique can perform both neutron imaging and spectrometry. To achieve this, the detector must be capable of resolving the path of the recoiling particle after having been scattered by an incident neutron. The neutron angular and energy resolution depends upon the precision with which one can determine the recoil proton direction and energy. When depositing their energy via ionization, protons exhibit a “Bragg peak,” which is a phenomenon where a large fraction of energy is deposited at the end of the proton’s track. Since the Bragg peak occurs at the end of the track, it can be used to determine the track’s orientation. The length of the track provides an estimate of the energy of the proton. By combining the proton energies and directions from a double neutron scatter, the energy and direction of the incident neutron can be determined in a way similar to a neutron scatter camera. This technique is, in principle, more precise since the path of the first recoil proton constrains the direction of the incident neutron to lie on a segment of a cone (an arc). This could lead to an improvement in angular resolution and thus improve signal to background.

One method that has been used for proton tracking uses a stack of crossed scintillating fibers to reconstruct the proton track [Mil03]. Recent results show that such instruments can operate at high energies ~20–250 MeV. At fission neutron energies, the smaller proton recoil energy available limits performance. The proton will fully deposit its energy in a very short distance, ~1 mm in a plastic fiber, and one needs several hits to determine a track. This requires the fibers to be small of O(100 μm). The sensitivity of this technique is thus constrained by limits on detection volume that can be obtained using crossed scintillating fibers of this size. High channel counts also lead to associated readout challenges. Since plastic scintillation fibers are sensitive to neutrons, gamma rays, and muons, discriminating backgrounds from cosmic muons and ambient gamma rays poses another challenge.

Time Projection Chambers—Another technology with potential to track recoil protons and thus image incident neutrons is the TPC, which was introduced in the *Neutron Detection Systems* section. TPCs consist of a gas-filled chamber with multi-wire proportional counters at the ends. A high electric field is held across the length of the chamber such that an ionization track left by a recoiling particle in the gas will drift the length of the chamber, where it is detected by the wires at the end. The horizontal directions of the track can be reconstructed by the location of charge deposition in the wires, while the vertical direction is determined by differences in the drift time in the gas. The resolution with which horizontal directions can be determined is limited by the pitch of the wire grid, while the inferred vertical direction is limited by the timing resolution of the measurement.

Because the recoil particle deposits less energy per unit distance in a gas, the length of the track will be longer than in a solid- or liquid-based recoil-particle tracking detector. This allows for a lower energy threshold with the possibility of tracking recoil protons from fission-energy neutrons. One of the drawbacks of a gas is the low density of target particles. This is especially problematic when requiring two scatters to fully determine the incident direction. Thus, to be sensitive in a multi-scatter regime, a TPC must be large or operate at very high pressures, and both factors complicate field deployment. Alternatively, TPCs can operate in a single-scatter mode where directionality is achieved via collection of multiple single-scatter events, thus reducing the requirement of enough stopping power to induce multiple scatters in a single event.

Because neutrons deposit the most energy on average to low-mass gasses, high-pressure hydrogen TPCs were first considered, but safety concerns have led to other gases. For example, alkane gases have been used to combat perceived safety issues and have the added benefit of higher hydrogen density compared to H_2 gas. Other potential drawbacks include the complexity of the readout system due to the large number of readouts and the possibility for microphonic noise in wire-based systems, although it is important to note that other readout methods exist, such as pad plane readouts.

The lower rate of energy deposition (dE/dX) of electrons (scattered by gammas), compared to nuclear recoils producing the same amount of ionization, could make a TPC less susceptible to gamma-ray backgrounds. Signal to background issues for these detectors are currently under study. Current development is underway to understand some of these issues and develop an instrument suitable for nuclear search and monitoring applications.

Identification of Shortfalls

Imaging systems hold the potential for significant advantages in terms of signal to noise because of their ability to examine both the spatial and spectral character of events. Despite this potential and a fairly mature technological state, imagers have experienced very limited deployment. The reason for this stems from two major deficiencies: efficiency and deployability. A third shortfall related to detection efficiency stems from the fact that imaging systems struggle to perform well over the full range of particle energies emitted by SNM.

Efficiency—The most pressing shortfall of conventional imaging systems is their general dearth of detection efficiency, imaging efficiency, or both at high gamma-ray and neutron energies. Although imaging methods generally have higher signal-to-noise performance than non-imaging techniques, the efficiency with which they collect and reconstruct events from both sources and background can be very low.

Efficiency presents challenges to different imaging systems in different ways. In Compton cameras, detection efficiency can be a challenge, and, in both Compton cameras and neutron scatter cameras, typical imaging efficiencies are less than 5–10% [Sei07]. Modulation systems can in principle maintain a large imaging efficiency, but modulation is challenging at high gamma-ray energies. If the efficiency of imaging systems, particularly spectroscopic systems, could be increased substantially, then imaging systems could play an important role in a variety of applications.

Deployability—Overall system size is an important constraint (but one that is highly application-specific) when considering deployability, and many gamma-ray and neutron imaging systems are intrinsically large. For instance, coded-aperture imaging systems for high-energy particles must have a minimum mask thickness on the order of the attenuation length of the particle to be detected (and preferably larger), which is of O(1–10 cm) for high-energy photons. This results in a large size that can impede their deployability, particularly in cases where mass is constrained. A similar scaling rule applies to neutron scatter cameras because the probability of a neutron scattering off of one detector element and being successfully detected in another is minimal. Unless a scatter camera is large and densely populated with detectors, the probability of interacting with more than one detector element is small. Secondary shortfalls associated with complexity challenges include the need for multiple channels and their associated instrumentation, complex readout software, ruggedness, and power consumption. Event reconstruction algorithms often require significant computational resources to mitigate the effects of artifacts that mimic source signatures. It should be noted that although these are significant, similar engineering challenges have been solved for imaging systems in other applications with deployments to fixed installations with considerable infrastructure, such as medical diagnostics. An important challenge remains, however, that is unique to SNM detection: namely the automated analysis of spectroscopic image data to provide actionable information without user input or expert analysis.

Dynamic Range—Gamma-ray and neutron emissions from SNM span a large range of energies, in the case of gamma rays from ~50 to 3,000 keV and in the case of neutrons from thermal energies to 10 MeV. Since imaging methods tend to exploit a particular interaction mechanism that is dominant over a specific energy range, imaging systems struggle to maintain sensitivity across this range. In the case of gamma rays, Compton cameras have maximum sensitivity at energies in between the dominant photoelectric and pair-production mechanisms. Modulation systems need to fully attenuate gamma rays in their masks and thus perform best at low energies. Analogous principles apply to neutron imaging systems where modulation techniques are well-developed for thermal neutrons, but there exist no effective modulation schemes for high-energy neutrons. Conversely, energetic neutrons have recently been successfully imaged with scatter cameras, but scatter technologies are useless for imaging at low energies.

Prioritized Investment Options

The fields of gamma-ray and neutron imaging are complex, and their combination with constraints of operational users creates perhaps the most difficult area in which to prioritize investment options. While many potential R&D avenues exist, the following options are those identified by a group of SMEs and prioritized by NA-22 to best meet the broad range of requirements. This prioritization scheme, which largely consisted of first ordering options based on their priority in the *SNM Movement Detection Portfolio—Technology Roadmap* and then by estimated impact levels, is listed in **Table 5**.

Table 5. Prioritized investment options for imaging methods.

Investment Option	Priority	Impact	Summary
Imaging systems not reliant on discrete detector elements	Medium	High	The largest deficiency of existing gamma-ray and neutron imaging systems is their lack of efficiency partially brought about by the need to modulate or segment detectors. Exploration of methods for the tracking of scattered particles without using individual discrete detector elements may create new systems that offer sufficient efficiency and angular resolution. One existing approach in this spirit relies on time projection chambers, but their gas-filled nature limits overall efficiency. Bubble chambers offer similar advantages in principle, and, if continuously sensitive bubble chambers could be devised, they would present a potential solution. Other possibilities include encoding angular trajectories in pulse shape.
Scatter cameras that track secondary particle production	Medium	Medium	Existing scatter cameras, both for neutrons and gamma rays, reconstruct a single angle of the incident particle being imaged. The resulting image reconstruction, based on cone projection, is an inefficient and noisy process. If both angles of the incident particle could be deduced, image reconstruction and source location could be performed more efficiently. By tracking the secondary particle produced in scattering events, it would be possible to determine both incident angles for the incoming particle—thus constraining its trajectory to a line instead of a conic surface. If methods could be devised to track protons (in neutron scatter cameras) and individual electrons (in gamma-ray Compton cameras), higher performance imaging devices could be constructed.
Simultaneous gamma-ray and neutron imaging	Medium	Medium	The detection of heavily shielded SNM or SNM at large standoff distances in the presence of natural radioactive background presents a challenging signal-to-noise problem. If an effective system could be developed to simultaneously image neutrons and gamma-rays, the signal-to-noise ratio might increase considerably to the point that only a few events would be necessary for positive detection of SNM. While two separate imaging systems achieve this same goal, the efficiency of such a system and its deployment challenges would be serious impediments. The development of imaging technology simultaneously sensitive to energetic neutrons and gamma rays would introduce a new capability.
Solid, high-energy neutron imaging systems	Medium	Medium	Existing high-energy neutron imaging systems rely on liquid organic scintillators as detector elements. While necessary to perform pulse-shape discrimination against interfering gamma rays, these liquid scintillators are difficult to deploy. Single-crystal organic scintillators, such as anthracene and *trans*-stilbene, could solve many of the problems inherent with liquid scintillators while simultaneously offering higher performance. The successful development of systems based on single-crystal organic scintillators requires concurrent developments in crystal growth and instrument development.

Photon Sources

Technology Requirements

Application of photon sources to the detection and characterization of SNM is a relatively new R&D objective. Requirements for field-deployed systems in nonproliferation are considerably different than the requirements under which today's laboratory systems were developed. The need to develop photon source technology outside of the laboratory led to the prioritization of both broad-spectrum and monoenergetic photon sources as first-priority items in the *SNM Movement Detection Portfolio—Technology Roadmap*.

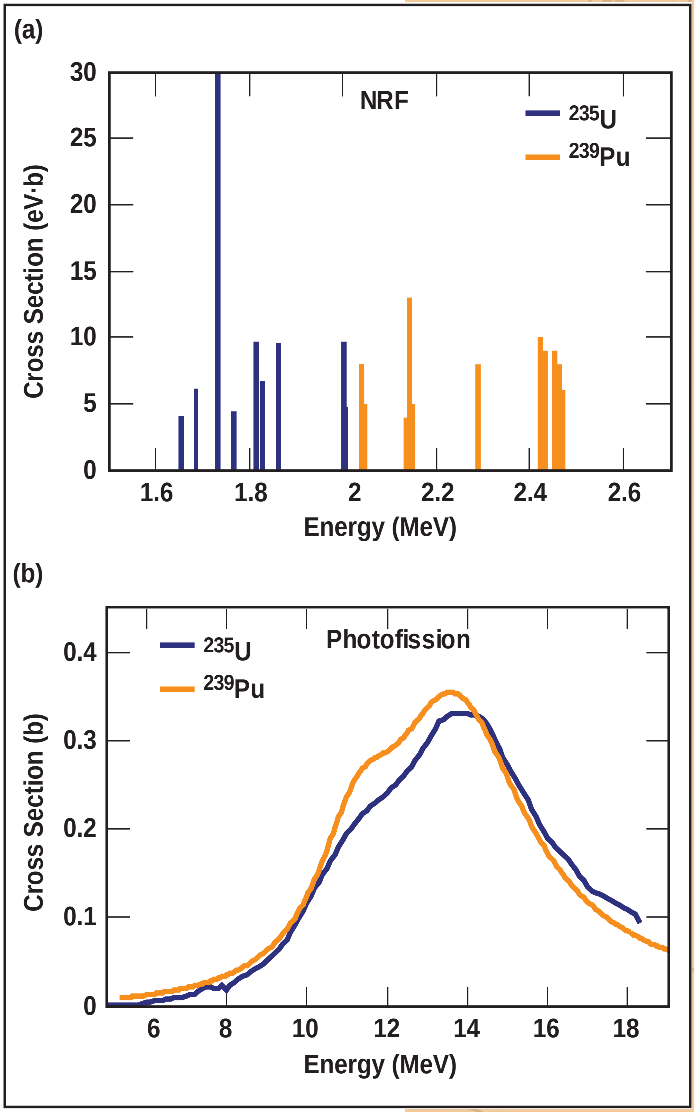

Figure 17. Cross sections for NRF (a) [Ber08] and photofission (b) [T2N09] as a function of energy. Note the different energy regimes associated with each process.

Photon energy is the most fundamental requirement for SNM detection, and sources must provide significant fluxes at an inspected object in the range of 1 to 3 MeV for nuclear resonance fluorescence (NRF) and in the range of 10–20 MeV to maximally induce photofission, as shown in **Figure 17**. Due to attenuation and energy downscattering through air, standoff applications may even require significantly higher energies. Control over the emitted energy spectrum is also an important requirement. For photofission applications, bremsstrahlung photons less than the photofission threshold energy will contribute to unwanted dose, while, for NRF, photons with off-resonance energies solely contribute to continuum background underneath regions of interest in detector response functions. These unwanted photons could be eliminated from the incident flux itself or via signal processing, e.g., time tagging.

An ideal photon source for photofission applications consist of no photons having energies less than ~7–8 MeV and with higher-energy photons in either discrete energy regions or with a continuum of energies providing direct and/or downscattered flux interactions in the 10–20-MeV photonuclear interaction region of interest. An ideal source for NRF applications will only allow photons within a narrow bandwidth surrounding discrete lines of interest to contribute to measured spectra. One method of achieving this is the development of tunable, quasi-monoenergetic sources with narrow bandwidths (defined as $\Delta E/E$) ideally of $O(10^{-4})$.

Photon Sources

Required photon fluxes vary considerably among applications, especially as a function of standoff distance, but, given that measurement times are typically of *O*(10–100 s), SNM detection in the field requires fluxes well above systems designed for laboratory-style analysis. Mainly for NRF signatures, but potentially for prompt photofission signatures as well, continuous-wave or quasi-continuous-wave operation is desirable due to the response time of high-resolution signature detectors. For pulsed sources, detector recovery can become a significant challenge requiring further development to enable accurate detection of these signatures. Standoff-detection applications impose the additional requirement of forward-directed photons with precision alignment.

Ultimately, sources must be integrated into operations that require transportability, provide limited physical space and infrastructure, and set operator dose limits. System-wide footprints of $O(1–5\ m^2)$ with power consumption of *O*(25 kW) will support portability. Reduced radiation exposure to both the environment and operators is mandatory, and reducing flux from photons that do not induce signatures of interest is thus an important area of development.

Survey of Field

Contemporary photon sources rely on acceleration of particles, either electrons or ions, and the subsequent conversion of their energy into photons. This process occurs in four generic stages. The first stage consists of an ion source that creates free electrons or ions. A low-energy accelerator, coupled to the electron/ion source, extracts the electrons/ions. The next stage accelerates particles to the desired energy via various electrostatic, radio-frequency, or plasma-based acceleration methods. Particle beams must then be transported or drifted to the final stage that converts the electron/ion energy into photons, most often by bombarding a target material. A few key parameters describe accelerator capabilities: the particle accelerated (electron/ion mass and charge), the final energy of the accelerated particle, the beam emittance (or focusability and energy spread), the average beam current, and, for delayed signal analysis, duty factor and/or repetition rate can be a critical factor.*

Several methods have been used to accomplish the first three stages and produce accelerated electron/ion beams. These include:

Linear Accelerators (LINACs)—LINACs are microwave-driven resonant-cavity devices that exploit the large electric field gradient for short-wavelength electromagnetic waves. When charged particles are injected into such a field, some of them (~¼ to ½) are accelerated to high energies by the microwave's electromagnetic field, at which point they can be extracted and used. LINACs are widely used for both electron and ion particle acceleration. Contemporary magnetron/klystron-driven electron LINACs can readily produce electrons at 10 to 20 MeV/m acceleration gradients with 50 to 250 μA average beam currents. Various transportable designs are commercially

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* Another quantity, the beam power, is the product of the energy and average current of the accelerated beam. For example, a 10-MeV electron beam operating with and average 10-μA beam current will generate a 100-W beam. Peak beam current is also a key parameter for some detection schemes, e.g., in "single-shot" detection.

available [Lin09]. Flexible design parameters enable LINACs to support many application-specific needs (e.g., **Figure 18**). For photon-inspection applications, LINAC performance is in practice limited by environmental dose management and available system power. Largely due to higher beam current needs and reliable operational performance, the S- and L-band frequencies have been common in LINAC designs; however, the use of X-band and higher-frequency LINAC systems can significantly reduce any overall inspection system design. A radio-frequency quadrupole (RFQ) linear accelerator is a more sophisticated device, and, for typical commercial, transportable applications, RFQs can provide up to 7-MeV ions with a peak current of ~25 mA [Acc09], yet it is still limited by dose management and available power. They are also considerably less rugged and require more maintenance.

Figure 18. A transportable, forward dose-controlled, photon inspection system prototype using a nominal 30-MeV LINAC mounted on a 2.4 × 1.2-m beam targeting assembly for standoff nuclear material detection. Figure courtesy of James L. Jones, Idaho National Laboratory.

Electrostatic Accelerators—Electrostatic accelerators operate by maintaining a fixed terminal voltage that attracts or repels charged ions. To maximize ion beam energy with a minimum terminal voltage, a "tandem" configuration can be used to double the ion energy. In the tandem configuration, electrostatic accelerators have two stages of acceleration—first "pulling" negative ions and then "pushing" positive ions that are created upon interaction with thin foils that strip electrons from the ion. Insulation of multi-MeV high voltages has traditionally been accomplished using high-pressure vessels that are large and massive. For this reason, near-term, transportable systems with electrostatic accelerators will be restricted to lower ion beam energies. Compact systems have been developed capable of accelerating protons up to 500 keV with average beam currents up to O(1 A) [Lud09]. These types of systems, such as the one shown in **Figure 19**, are generally acceleration gradient-limited due to breakdown complications from the large applied voltage, but are also limited by the lack of compact high-voltage power supplies.

Cyclotrons—In the cyclotron, particles are confined to a circular trajectory, typically using electromagnets, until they reach sufficient energy. This method has the advantage of continuous acceleration, since the particle can remain in transit almost indefinitely. Another advantage for higher-energy applications is that a circular accelerator has a smaller footprint than a linear accelerator of comparable energy and power (i.e., a LINAC must be extremely long to have the equivalent high-energy acceleration capability of a cyclotron). Commercial, multi-meter-scale cyclotrons with masses of O(10,000 kg) accelerate protons up to 30 MeV with average beam currents up of O(1 mA) [Adv09]. Using state-of-the-art magnet technology, including variation of the cycle time to accommodate increasing velocity and/or superconducting technologies, these systems can produce higher-energy particles within a reasonably compact configuration.

Photon Sources

Laser-driven Wakefield Accelerators (LWFAs)—These accelerators have received recent attention because of their ability to accelerate electrons to very high energies in very short distances. The unique LWFA technology exploits the radiation pressure of an intense laser to excite a space charge wave in a plasma. The induced electric field has been demonstrated to accelerate electrons to 1,000 MeV in distances of 3 cm as compared to distances of O(30 m) for the aforementioned conventional accelerators [Lee06]. Present electron energy spread and stability are of O(1–3%) [Rec09]. It is expected that detailed control of electron injection and accelerator structure will improve beam quality in the next several years, but duty factor, average beam power, and minimizing ion energy spread are all major challenges that must be addressed before applications will benefit from LWFAs. LWFAs have a demanding laser pulse-length requirement, ~50 fs, that is required to match the plasma wake.

Figure 19. A 165-keV electrostatic accelerator with high-voltage power supply (in background on left). Figure courtesy of Arlyn Antolak, Sandia National Laboratories.

After producing electron/ion beams, several techniques are available for conversion into photons. The simplest approach exploits the bremsstrahlung process and produces a broad energy spectrum. A more speculative approach, which is also broad in its energy distribution, exploits the fusion process. Production of monoenergetic photons is a significantly more challenging proposition. Two production methods, one based on particle-induced nuclear reactions and the other laser Compton scattering, are currently under development.

Bremsstrahlung—Perhaps the most common method of high-energy photon production is the bremsstrahlung process whereby energetic electrons interact in an electron/photon converter material and emit a portion of their energy in the form of photons. Bremsstrahlung sources produce photons with an exponentially decreasing energy spectrum that extends up to the maximum energy of the electron. The efficiency of energy conversion varies, and the fraction of converted energy increases with electron energy and is proportional to the square of the converter's atomic number (Z^2). If the ion-to-photon interaction in the converter is directionally controlled, the emitted photons will have a forward-directed flux with decreasing opening angle as the electron beam energy increases. It should be noted that the converter material could incorporate photon-energy filtering methods and even consist of the object under inspection or surrounding objects, if dose constraints can be adequately managed.

Fusion—In principal, "mirror-type" fusion reactor designs using magnetically confined plasmas could isotropically generate photons with a Maxwellian energy spectrum. Such an energy distribution would induce more photofissions per unit dose than a bremsstrahlung spectrum. While large fluxes of relatively low-energy photons have been demonstrated with this type of device [OTo83], the systems are of O(10 m) in size and cost billions of dollars. The feasibility of system scaling to generate photons of O(10 MeV) remains unclear since such photon energies have not been the focus of fusion technology development. In addition, with a harder photon flux comes more difficulty in meeting shielding requirements for a transportable system.

Particle-induced Nuclear Reactions—Reactions between accelerated ions and low-Z materials emit monoenergetic photons that correspond to specific states within the compound nucleus. These nuclear reactions require a stable (or long-lived) target nucleus and an incident particle beam that can be easily produced and accelerated to an appropriate energy—often corresponding to a reaction's resonance energy. Over 500 nuclear photon-emitting reactions have net energy production greater than the photofission threshold energy, but the vast majority of these reactions produce dual-particle emissions consisting of both photons and neutrons (or other particles). Pure photon sources can be generated from proton-capture reactions with low-energy narrow resonances, and **Table 6** identifies those most applicable to photofission. One drawback of reaction-based photon sources is that, aside from those mentioned above, the emitted photons are nearly isotropic. Only a small fraction of emitted photons are thus incident on the object of interest—a fact exacerbated in standoff applications. Achieving large fluxes at the object of interest requires directing copious amount of protons onto the reaction target. This creates significant engineering challenges in target design.

Laser Compton Backscatter—The head-on scattering of relativistic electrons and laser photons produces a forward-scattered beam of nearly monoenergetic photons. The energy of the scattered photon ($h\nu_{\text{scatter}}$) is a function of the electron energy (via γ) and laser frequency ($h\nu_{\text{laser}}$):

$$h\nu_{\text{scatter}} = 4\gamma^2 h\nu_{\text{laser}} \; .$$

Hence, higher electron energies of O(100–1,000 MeV) will be required to achieve the desired energetic photon beams via any laser Compton backscatter-conversion process. For example, scattering between 800-MeV electrons and 1-µm laser light produces a beam of 15-MeV photons. Photon beams produced in this process have two attractive characteristics. First, the beam divergence can in principle be small enough to project a cm-size spot at a 100-m standoff distance. Second, if both the electron beam and laser

Table 6. A sampling of low-energy, proton-capture reactions capable of producing pure photon beams. Bold font indicates gamma-rays emitted with the highest probability.

Reaction	E_γ (MeV)	E_p (keV)	σ (mb)	Width (keV)
^{7}Li$(p,\gamma)^{8}$Be	**17.7, 14.8**	441	6	12
^{11}B$(p,\gamma)^{12}$C	16.1, **11.7**, 4.4	163	0.16	7
^{13}C$(p,\gamma)^{14}$N	**8.06**, 4.11	550	1.44	33
^{19}F$(p,\alpha\gamma)^{16}$O	7.1, 6.9, **6.1**	340 484 597 672	160 32 7 57	3 1 30 6

are monoenergetic, the resulting photon bandwidth, defined as $\Delta E/E$, can be of $O(10^{-3})$ and potentially smaller. Small photon bandwidths lead to a large signal-producing photon flux per unit dose imparted to the surrounding environment, especially when compared to a bremsstrahlung source. Laboratory sources have produced 10^6 photons/laser pulse on an item of interest at multi-MeV energies with a bandwidth of ~0.1 [FEL09]. At lower energies, laser Compton scatter sources produced 10^9 photons/laser pulse with a bandwidth of 0.1 at 70 keV [Gib04]. More recent work produced 10^6 photons/laser pulse at 700 keV [Alb08].

Time-Tagged Sources—It is possible to have both monochromatic and broad spectrum sources simultaneously. The method of "tagging" photons (either bremsstrahlung-generated or laser-Compton scattered) has been developed in several nuclear physics labs since the 1970s (e.g., see [Vog93][Elv08]). Photon tagging involves analysis of the scattered electrons after photon production. By measuring the energy/momentum of the photon-creating electrons, the photon energy and time of production can be deduced. This technique has contributed an enormous amount of information to the world's photonuclear data, and it enables simultaneously using the entire spectrum for photofission measurements, for example, while also defining quasi-monoenergetic portions of the spectrum that are relevant for NRF. Photon tagging requires high duty factor electron beams. Bremsstrahlung-based tagging systems typically employ a magnetic spectrometer to momentum-analyze the photon-creating electrons and to dump the non-interacting electron beam. The energy resolution, $\Delta E/E$, of each photon-beam channel depends upon properties of the electron spectrometer (e.g., momentum dispersion, position resolution of the electron detectors in the focal plane, magnetic field non-uniformities and fringe fields), the electron beam emittance, and possible sources of electron multiple-scattering in systems that are not completely vacuum-coupled. Resolutions of $O(10^{-3})$ to $O(10^{-2})$ at central tagged photon energies in the range from 10 MeV to several hundred MeV are typical. The maximum useful tagging throughput depends upon the response time of the electron spectrometer, the coincidence resolving time between the tagger and detectors registering products of the photon-induced reaction of interest, and the throughput of the data acquisition system. Tagged photon intensities reported in the literature range from $O(10^7)$ photons/second integrated over a 3-MeV window centered at ~10 MeV [Elv08] to $O(10^8)$ tagged photons/second in a 62-channel tagger spanning ±20% in energy around 100 MeV [Vog93].

Identification of Shortfalls

The aforementioned requirements will challenge technology development in terms of producing necessary photon fluxes, managing overall system size and mass in conjunction with developing compact and efficient power supplies, and limiting environmental dose. Technology development to date has produced progress in each of these areas, but progress has been spread over a range of technologies. A comprehensive photon source solution does not yet exist. For example, while monoenergetic photons can reduce the dose on target required for a successful inspection, they have to date struggled to deliver sufficient photon fluxes to the item of interest. Bremsstrahlung sources are approaching the capability to deliver sufficient broad-energy fluxes at standoff distances, but they must be made compact with reduced power consumption. In total, the shortfalls that must be overcome reside in four broad areas:

Photon Flux—Increasing flux generally means increasing the beam energy and current delivered by an accelerator. However, there are practical limits to any accelerator design, at a given energy, for which further beam current increases are not feasible. Hence, the beam current and accelerated electron/ion energy are closely intertwined by physical design constraints, rather than being independently tunable parameters. Near-term advances toward efficient power supplies, increased acceleration gradients, and robust target designs are needed to advance capability. For bremsstrahlung sources to be feasible in photofission applications, enhanced acceleration gradients are needed for compactness, low-energy photon production management is needed for dose control, and higher beam currents may be required for interaction optimization; for NRF measurements, the bremsstrahlung sources must operate at high frequencies to emulate quasi-continuous-wave sources. In the realm of nuclear-reaction-based sources, the primary near-term technical challenge revolves around stability of the reaction target. Achieving reasonable fluxes on items of interest requires that significant amounts of beam power be placed on a production target to achieve a reasonable photon flux. While bremsstrahlung sources must match higher beam currents with higher beam energies, effective ion sources must find an appropriate balance between high-energy, low-current operation and low-energy, high-current operation. In the long term, the development of pseudo solid-state or laser-driven accelerators may enable combined high-energy, high-current operations.

Tunable, Monoenergetic Beams—While optimism surrounds the potential of laser Compton scattering to provide high fluxes of monoenergetic photons, shortfalls exist in the ability to produce tunable beams that are stable during day-to-day operation. Continued development relies heavily on advances in lasers that are compact, high power, energetic of O(1–10 J), and have short pulse widths of O(1 ps). The electron-laser interaction also requires further engineering to increase flux and decrease the bandwidth. In the long term, transitioning these sources out of the laboratory requires advances in accelerator development to reduce overall system size.

Transportable and/or Fieldable Designs—Today's accelerator technologies are over 60 years old and were developed for laboratory operation. For example, high-energy electrostatic accelerators are physically large and massive to reduce breakdown between acceleration stages. Accelerators of all types must now be transformed into compact, efficient systems with low overall costs. Necessary advances include development of compact high-voltage power supplies and associated power-conditioning stages, thermally limited cathode photoguns to support high-repetition-rate applications, and radio-frequency and non-radio-frequency acceleration waveguides and cavities that reduce size. In the long term, high-gradient LINACs or laser-driven accelerators may be important to provide high gradients and, hence, be important in achieving small footprints.

Dose Control—All electron and ion accelerators will produce radiation dose at the photon source, at the item of interest, and in any intervening material between source and interrogation target. In delivering the necessary photon fluxes, it is expected that background-type dose limits will be exceeded. Thus, essentially all applications will require radiation control, and shielding (coupled with technology-specific enhancements) emerges as one of the paramount issues for accelerator-system design.

Prioritized Investment Options

The development of monoenergetic and broad-spectrum photon sources were both first-priority items in the *SNM Movement Detection Portfolio—Technology Roadmap*. The role of these sources in nonproliferation is evolving, with feasibility studies for active interrogation presently underway that will inform future investments in source technology. In recognition of this state, the prioritization by NA-22 of investment options identified by a group of SMEs (**Table 7**) consisted of estimated impact levels derived from the capability to produce a balanced improvement of the technology as a whole.

Table 7. Prioritized investment options for photon sources.

Investment Option	Priority	Impact	Summary
Next-generation accelerator concepts	High	High	Development of photon sources meeting all of the requirements of being monoenergetic, tunable, high flux, and mobile may require investment in accelerator concepts different from those emerging from contemporary R&D. Significant potential may reside in recent developments, such as in the case of powerful, ultra-short laser systems that have permitted study of a new approach to generating energetic, forward-directed photon beams. Similarly, the high-energy electron accelerators needed for laser Compton scatter sources may be greatly reduced in size using LWFA technology. Further development of these emerging accelerator technologies will require long-term investments but also offers the potential of revolutionary accelerator concepts. Other accelerator concepts may be considered with one potential example being photon production via direct laser-material interactions within materials near or surrounding an interrogation target.
Monoenergetic, tunable sources	High	High	Tunable photon sources with extremely narrow bandwidths of $O(10^{-5})$ would dramatically increase the signal per photon in NRF applications if the energies could be matched to NRF states. Such sources would also reduce continuum backgrounds and minimize dose per incident photon. Development efforts should continue to further decrease electron energy spread, increase laser photon flux, and decrease photon bandwidths. One short-term objective is the investigation of methods to increase and control laser-electron interactions.
Development of compact, mobile photon sources	High	High	Development of sources for applications with stringent size and mass constraints will require considerable advances in present source technology. Human-portable systems will be especially challenging since battery power operation may be required. For these sources, near-term goals focus on photofission exploitation. Tunability is thus not a requirement, but minimal dose is. A target size for such systems is in the range of 100 kg and 1 m^3. In the case of bremsstrahlung sources, compact power supplies with more-efficient, higher-frequency acceleration gradients and enhanced higher energy, electron-photon production with low energy photon tailoring are needed to reduce system size and weight. In the case of nuclear-reaction-based sources, high-current power supplies must be developed, e.g., in the range of 180 kV and 1 A. Further work should also identify other viable nuclear reactions, assess optimal photon production targets and material types (thermal properties, cross section, manufacturability, etc.), and address operator shielding constraints.
Development of high-energy, quasi-monoenergetic sources	High	Medium	Existing technology provides the capability to exploit photofission but only using bremsstrahlung-based accelerators that impart significant dose to the interrogation target and the ambient environment. Reducing the dose, while maintaining high photon flux on target, is an important objective that could be achieved through the development quasi-mono-energetic sources (~0.1 dE/E) residing in the 6–15-MeV range.
High-repetition-rate LINACs	High	Medium	Increased photon flux from LINACs could be achieved via operation at high repetition rates of O(1–10 kHz). Such operation will allow the full exploitation of both prompt signatures (occurring during or immediately after an interrogation pulse) and delayed signatures (occurring between inspection pulses or after the interrogation process). This includes NRF signatures that are at presently accessible only with continuous-waveform accelerators. High-repetition-rate LINACs would also advance time-tagged photon systems that have not yet been developed for high-flux applications. Given a fixed rate of charge injected per unit time, it is preferably, for the purposes of reducing pileup and/or accidental coincidences), to distribute such charge over a relatively large number of small pulses so that the peak rate in any give pulse is minimized.

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Neutron Sources

Technology Requirements

Requirements for neutron sources derive from the expected applications for detection, identification, and characterization of interrogation targets in close proximity using portable systems that can be setup in short time periods (e.g., minutes). The application of neutron sources to this end in fixed settings has a long history in nuclear material assay, waste measurements, and pulsed neutron analysis [Goz81]. The primary difference between the constraints of these environments and those of shielded SNM detection revolves around measurement conditions, measurement time, standoff distance, and the fidelity of results (e.g., in terms of detection, identification, or quantification).

Requirements for proximate detection, where an interrogation target resides a few meters or less from the source, generally fall into two categories. The first category stems from applications where neutron sources are delivered to field settings, such as in maritime boarded search. Since measurement times are of O(100–1,000 s) and standoff distances are of O(1 m) in this case, neutron yields greater than $O(10^9/\text{s})$, in either pulsed or continuous modes, are a reasonable goal for systems development. This goal is subject to the constraint that individual components of lightweight systems must be of O(10 kg) or less, and the overall size of each component must be compatible with backpacks or shipping cases, with a goal for a total system package of $O(1{,}000\ \text{cm}^3)$. Sources must operate on battery power but not necessarily for extended periods of time (e.g., days).

The second category includes fixed-site applications, such as treaty-monitoring environments, that impose requirements more similar to traditional assay environments. In these cases, interrogation targets reside within several meters, but interrogation targets may be denser and often filled with hydrogenous material. This, combined with reduced measurement times of O(10–100 s), requires large neutron yields of $O(10^{11}/\text{s})$ in systems capable of operating in a continuous mode or pulsed mode up to 10 kHz. Neutron sources must still be transportable, but they need not operate on battery power. For temporary deployments, minimizing system footprint is important, and a reasonable goal is the reduction of the footprint to $O(1\ \text{m}^2)$. Extending the operational lifetime beyond that of current generation systems, in the $O(10^7\ \text{s})$ range, to approach $O(10^8\ \text{s})$ is another important goal that requires significant advances to various system components.

Longer-term requirements stem from the ultimate desire to use neutron sources in standoff applications that require multi-MeV sources with directional beams. It may also be necessary to perform associated particle tagging to further define the direction of outgoing neutrons. The ability to pulse the beam for background reduction might also be necessary, further complicating the detector systems used in associated particle imaging neutron sources. Production of tagged beams at higher fluxes, e.g., from a $10^9/\text{s}$ generator, requires detectors that are capable of detecting alpha particles at the same rate; in pulsed systems, the instantaneous beam currents are significantly higher and avoiding pileup becomes more challenging. Alpha particle detectors must then be segmented, extremely fast with nanosecond-scale recovery time, and the data acquisition system must operate on a clock rate of at least 100 MHz.

Survey of Field

Neutrons must be produced in nuclear reactions via spontaneous fission of actinides such as californium or curium; reactions between hydrogen, helium, and other light nuclei; or even the induced fission of SNM in nuclear reactors. Neutron source concepts suitable for use in SNM detection include radioisotope neutron sources, vacuum-sealed charged particle accelerators, vacuum-pumped charged particle accelerators, accelerator photo-neutron sources, and plasma-fusion devices.

Radioisotope Neutron Sources—Materials that undergo spontaneous fissions, such as the actinide nuclei ^{238}Pu, ^{240}Pu, ^{242}Cm, ^{244}Cm, and ^{252}Cf, constitute one class of neutron sources. The most common material in use is ^{252}Cf, which has a half-life of 2.7 years and a high specific activity compared to competing isotopes. The neutron energy spectra from spontaneous fission sources are typically peaked around 1 MeV with mean energies near 2 MeV and a characteristic fission energy distribution, as shown in **Figure 20**. In addition to neutrons, the fission process also leads to energetic gamma rays and heavy, energetic fission fragments. All of the particles are emitted isotropically. Detection of either the gamma rays or the fission fragments can be used to "tag" the outgoing neutrons with a coincident signal. Spontaneous-fission sources are deployed to industrial settings where the advantages of zero power consumption, minimal weight, reduced size, and reliability are critical. Future availability of these sources may be problematic since the only domestic production of ^{252}Cf takes place at Oak Ridge National Laboratory [Mar99], and the future of the production program is not guaranteed.

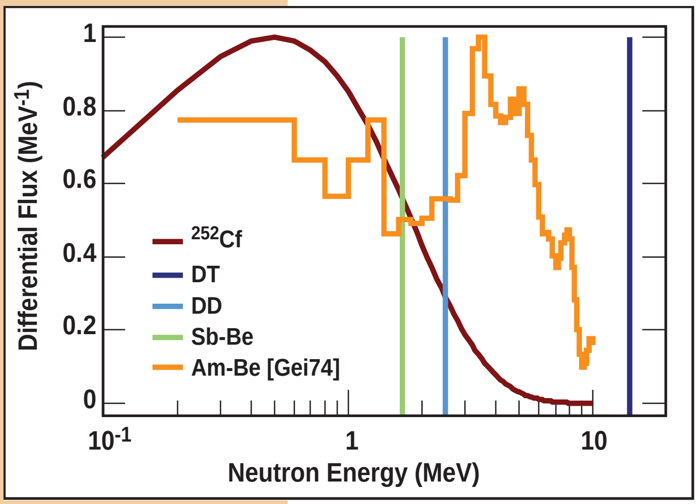

Figure 20. Comparison of normalized neutron energy spectra emitted by various nuclear reactions. Note that energies for the DD and DT reactions correspond to emissions at zero degrees.

Another class of radioisotope-based neutron sources consists of those that rely on (α,n) reactions. In these sources a radioisotope that decays with the emission of alpha particles is mixed together with a low-Z material that emits neutrons upon capture of the alpha particle. ^{9}Be is most common, but other target materials such as ^{7}Li, ^{10}B, and ^{11}B are present in specialized sources. Typical alpha-emitting nuclei used in these sources include ^{238}Pu, ^{239}Pu, and ^{241}Am. Since the energy of emitted alpha particles is isotope-dependent and target nuclei have different reaction thresholds, each (α,n) source produces a neutron energy spectrum having distinct and non-continuous neutron energy distributions. This is a distinct contrast with the smoothly varying distribution of the spontaneous fission sources. These sources emit gamma rays as well, e.g., the 4.44-MeV gamma ray from ^{9}Be. Due to the mixing of the alpha-emitter and the target material, all of the particles are emitted isotropically. Beryllium comingled with either plutonium (PuBe) or americium (AmBe) is by far the most common source of this type since beryllium has a large (α,n) reaction cross-section and produces the highest-energy neutrons. These sources are commercially available and common to applications such as well logging [QSA09]; however, a relatively large mass of actinide material of O(1 g) is required to make sources having neutron yields greater than $O(10^7/s)$, which necessitates addressing unique safety and security issues. The production, transportation, use, storage, and disposal of these sources are becoming problematic. For example, many high-intensity PuBe sources have been developed that contain up to 50 g of plutonium, and even the use of americium-based sources is rapidly becoming problematic due to increased security concerns during transportation and use.

Vacuum-sealed Charged Particle Accelerators—A distinctly different source of neutrons uses vacuum-sealed charged particle accelerators to exploit the ^{2}H(d,n)^{3}He (DD fusion) and ^{3}H(d,n)^{4}He (DT fusion) reactions, as well as the less-common ^{2}H(t,n)^{4}He and ^{3}H(t,2n)^{4}He reactions. DD fusion generates a quasi-monoenergetic neutron spectrum at 2.5 MeV; DT fusion generates a quasi-monoenergetic neutron spectrum at 14.1 MeV. Both reactions are primarily isotropic in nature, although the rate and energy have notable angular dependencies in the DD spectrum. Alternatively referred to as electronic neutron generators (ENGs) or sealed-tube neutron generators (STNGs), devices in this category incorporate small particle accelerators with acceleration gaps measuring less than a few centimeters in length, as shown schematically in **Figure 21**. They have internal, solid-state vacuum pumps that serve the dual purposes of maintaining vacuum inside the accelerator tube while also regulating the deuterium/tritium gas pressure within the ion source. An ion source produces a beam of deuterium and/or tritium. Extracted ions are accelerated and directed into a metal hydride target loaded with deuterium and/or tritium. Typical accelerating potentials for these devices are in the 50 to 350 kV range, while typical ion beam currents are in the 0.05 to 5 mA range. Sources possessing only deuterium are more desirable from a logistical standpoint, but tritium has significant performance advantages since neutron-production yields are 50–100 times greater than those from comparable DD systems. Further, the higher-energy neutrons from the DT reaction have greater penetration depth, but they produce high-energy gammas in non-fissionable material that may cause

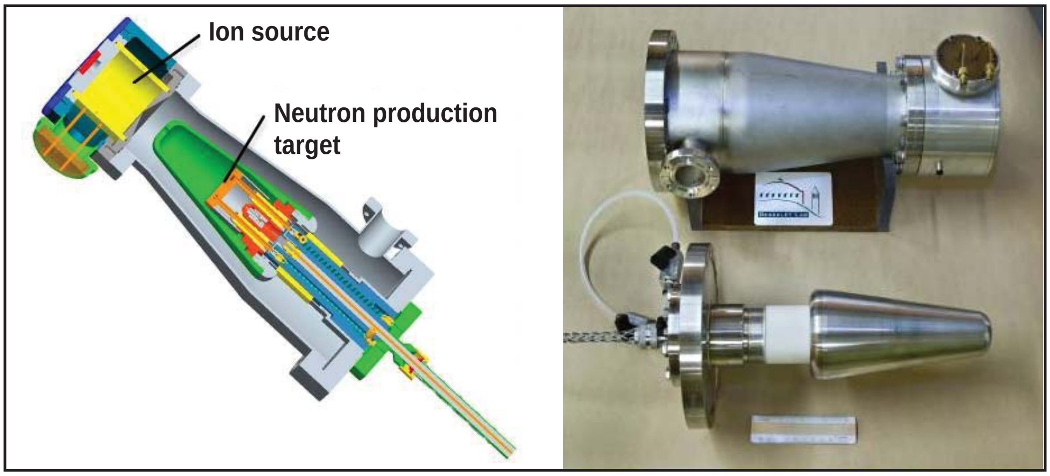

Figure 21. Schematic and photograph of compact neutron generator under development. Figure courtesy of Bernhard Ludewigt, Lawrence Berkeley National Laboratory.

interference with some SNM detection methods. A potential drawback with the use of DT systems for SNM detection is the possibility of creating the beta-delayed gamma-ray-emitting isotope ^{16}N (half-life = 7.13 s) in oxygen via the reaction $^{16}O(n,p)^{16}N$, which can act as in interference under some circumstances when beta-delayed fission product gamma-ray data is collected [Sla03].

Commercially available ENGs range from portable systems of $O(10^4\ cm^3)$ that generate yields of $O(10^8/s)$ to fixed-installation systems with masses of 1,000 kg that produce yields up to $O(10^{10}/s)$ [The09]. Higher-yield DT-based ENGs, with fluxes exceeding $10^9/s$, typically require active cooling to dissipate heat generated in the ion source and/or at the target. ENGs can be built as rugged, battery-powered, portable units. Instruments in this class operate in either continuous or pulsed mode with typical pulsing frequencies ranging up to 20 kHz. Having been widely produced by commercial vendors over several decades [Chi03], they exist in specialized form factors. Units for down-hole well logging in the oil exploration industry are typically packaged in long tubes with diameters of ~5 cm. In round numbers, these units are widely available in packages with total volumes of $O(10^4\ cm^3)$ and masses of approximately 10 kg.

Vacuum-pumped Charged Particle Accelerators—A closely related but significantly different class of neutron source relies on charged particle accelerators that are not vacuum sealed but have active vacuum pumps to maintain the internal vacuum within their accelerating column. At the simplest level, one category of this class of devices is essentially the same as the ENGs described above, using deuterium and/or tritium, but with external vacuum pumps. Today, vacuum-pumped ENGs almost exclusively use deuterium, due to hazards of tritium release.

Accelerators in this class can also produce neutrons using reactions of hydrogen isotopes with low-Z nuclei such as in the $^7Li(p,n)^7Be$ and $^9Be(d,n)^{10}B$ reactions. The (p,n) or (d,n) charge exchange reactions require energies of $O(1\ MeV)$ while (d,pn) deuteron breakup reactions require energies of $O(10\ MeV)$. These high energies, which are not attainable in STNGs, enable the selection of a reaction for characteristics including forward-peaked yield, high-reaction cross section, and the ability to tune the ion energy to produce a range of desired neutron energies. Neutron beams can be formed using inverse kinematics at energies of $O(10\ MeV)$ where the large momentum of the incident ion leads to forward kinematic focusing of the reaction products, e.g., accelerating the ^7Li ion rather than the proton in the $^7Li(p,n)$ reaction. A wide variety of accelerator systems have been developed including electrostatic accelerators, cyclotrons, and linear accelerators. Several commercial vendors offer systems for accelerator mass spectroscopy, surface analysis, material characterization, and medical isotope production. While these systems are suited for laboratory installations and are often capable of producing a variety of beams, they typically require a large, fixed infrastructure. Systems utilizing (p,n) and (d,n) reactions are capable of producing large neutron yields of $O(10^{13}/s)$ with lifetimes of $O(10^7\ s)$ [Acc09].

One type of charged particle accelerator found in an increasing number of industrial and field applications that exploit these reactions is the RFQ accelerator. RFQs are compact, robust, and well-suited for producing beams of protons and deuterons of $O(1\ MeV)$. RFQ technology can accelerate high beam currents and is now being offered for medical isotope production; one vendor offers a multi-MeV system in a trailer for portable radioisotope production [Acc09]. RFQ accelerators have also been designed and built for generating 6 to 8 MeV, forward-directed, high-intensity neutron beams via the DD fusion reaction for cargo screening applications [Hal07]. While they have advantages compared to other accelerators such as cyclotrons that require heavy magnets, or electrostatic accelerators that require significant spacing between components due to the multi-MV applied voltages, RFQ accelerators still require significant infrastructure. For methods that require beams in the MeV range, RFQ-based systems are attractive choices.

Another notable accelerator type in this category is the compact cyclotron. While conventional cyclotrons are large and heavy instruments due to the use of conventional electromagnets, new superconducting magnet designs have been proposed that may change this situation. Recent design work suggests the possibility of building a cyclotron using superconducting magnet technology capable of producing a 100-μA proton beam accelerated to 10 MeV. Such a system could produce a neutron output of 10^{10}/s with a mass of O(100 kg) [Ant08].

At the extreme end of the spectrum, the particle physics community is pursuing new technologies such as laser wakefield acceleration, which can produce accelerating gradients orders of magnitude larger than achievable with conventional accelerating cavities driven with RF amplifiers. Such technologies, once further developed, may offer opportunities for new particle beam sources in the future. While neutron beams have been produced for several experiments in nuclear physics, many of these beams are produced using spallation reactions on high-Z targets with subsequent collimation to form the beam rather than using the kinematics of the reaction [Blo07]. Only a few university laboratories have routinely produced neutron beams of O(10 MeV) for research applications.

Photoneutron Sources—Photons stimulate neutron emission when comingled with materials possessing neutron binding energies less than the energy of the photons. One method exploiting this phenomenon incorporates high-energy gamma-ray-emitting radioisotopes with low-Z target materials [Wat47]. The quasi-monoenergetic nature of the neutron energy spectrum of these sources is often particularly advantageous, but the neutrons are emitted isotropically. These sources most often use deuterium ($E_{threshold}$ = 2.23 MeV) or beryllium (E_n = 1.67 MeV) as target materials. The most common photon source is ^{124}Sb, which has a 60-day half-life. These photoneutron sources are not in widespread use; they possess significant drawbacks associated with their intense gamma-ray flux (which creates deployment challenges) and their short-lived gamma-ray-emitting isotopes (which must be replaced on a regular basis). The practical use of these sources in SNM detection scenarios is limited.

Another method of photoneutron production replaces the gamma-ray source with a high-energy electron accelerator that generates high-energy x rays (via a high-Z target). Materials with low neutron binding energies such as deuterium and beryllium are most commonly employed as conversion materials. For high neutron yield, high-current electron LINACs with beam energies above 6 MeV are typical, and the application of pulsed accelerators allow for time-of-flight spectroscopy. In these systems, high-intensity photon fields also exist, which may either be advantageous or disadvantageous depending upon the SNM detection method. An alternative is high-energy, sealed-tube electron accelerators that provide modest neutron production. Unlike most of the techniques using ion beams, this technique tends to produce neutrons with a broad energy spread, which is not particularly advantageous for most SNM detection scenarios [Lak08].

Plasma-Fusion Devices—The last class of neutron sources considered here are those that generate neutrons directly from plasma fusion. One example is the inertial electrostatic confinement device that uses electrostatic and sometimes magnetic fields to generate and confine deuterium and/or tritium plasma and induce fusion. These devices may be arranged in spherical or linear geometries. In an inertial electrostatic confinement device, ions accelerate across a low-pressure gas volume many times, producing neutrons in DT or DD reactions. These devices have the potential to operate in sustained modes of operation for very long periods of time. While similar to ENGs in their neutron generation characteristics, some drawbacks are their larger size and far greater complexity when compared with ENGs. Neutron yields exceeding 10^7/s have been achieved in open vacuum-pumped DD systems [Yos07]. These devices are not in widespread use, with one likely reason being that they require more than ten times the power per neutron compared to conventional ENGs.

Another type of neutron source using direct fusion is the plasma focus device [Kra89]. This type of neutron source uses pulsed-power technology to generate extremely high-current electrical arc plasmas between electrodes. Deuterium and/or tritium gas is either naturally present in the cavity between the electrodes or stored on the surfaces of the electrodes prior to discharge. A distinct performance advantage of these sources is the fact that they produce neutrons in short pulses with characteristic widths of O(1 ns). A distinct disadvantage of this type of neutron source is that they require regular maintenance to replace worn components; in particular, the operating lifetime of the electrode components is rarely longer than a few hundred shots.

Identification of Shortfalls

Detection methodologies using neutron sources are not fully developed for nonproliferation applications, but it is fair to say that existing technology that is field-deployable (for oil-well logging, density gauges, or SNM detection) and technology that is readily used in the laboratory for the production of neutrons both have shortfalls when considered for use in SNM detection in a range of scenarios spanning person-portable methods to standoff detection. The shortfalls associated with contemporary technology are thus qualitative at present and subject to further refinement pending more detailed definitions of the systems that will use them and the applications in which they will be used. While neutron source instrumentation shortfalls cannot be assessed in detail in the absence of a good understanding of the problems to be solved and the methods to be employed, major increases in neutron flux, generator lifetime, generator size, push-button use, neutron energy distribution, neutron directionality, etc. will require substantial improvements in any of the major components of neutron generators including power sources, targets, accelerating methods, and ion sources.

Increased Neutron Production—Present commercial products, in particular those that are portable, are limited to fluxes of $O(10^8/\text{s})$ and possess lifetimes of $O(10^7\ \text{s})$ when operating at these rates. The need to increase neutron production rates is thus both a combination of greater neutron yield and operational lifetime while maintaining the same mobile capabilities. Increasing the neutron yield is not simply addressed by scaling present systems but will require improvements in high-voltage power supplies, target design, and accelerated ion beam quality. High-yield sources will require more capable power supplies and support systems that can be made available in fixed installations or transportable systems. For example, a technical barrier to increased flux is target stabilization that requires active cooling in the case of metal hydride targets and other nuclear reaction targets. Increasing the atomic fraction of the accelerated ion beam over current commercial technology is another parameter that would increase neutron flux.

Portability—Exploitation of neutron interrogation in some applications of particular interest to nonproliferation requires person-carried and vehicle-mounted systems. Present technology does not meet size, mass, and power-consumption requirements at required fluxes. One underlying issue with all present-day sources is the power supply. Even with major advancements in conserving power during the production of neutrons, power supplies are still the largest component of all of the existing methods.

Directional Beams—Delivering high-intensity neutron fluxes to targets at standoff distances while limiting radiation dose to nearby personnel and the environment requires intense and highly directional beams. While the DD reaction is forward peaked at energies of a few MeV, a large fraction of the total neutron output is emitted outside of a 15° forward cone, thus making these sources unsuitable for standoff applications. Alternate methods exploit kinematics and heavier beam ions to induce directionality. Producing directional beams using these reactions requires production of ion beams with energies greater than 10 MeV. At these energies electrostatic accelerators are not suitable, and conventional cyclotrons are large, fixed in location, and require extensive infrastructure. RFQ accelerators, other linear accelerators, and superconducting cyclotrons may reach the needed energies and the other associated requirements for deployment in nonproliferation applications, but the engineering design issues required to achieve this are challenging.

Prioritized Investment Options

Development of compact neutron generators for field deployment is a fairly mature field, especially when compared to photon sources. Due to their utility at inducing fission, development of accelerator-based neutron sources was a first-priority item in the *SNM Movement Detection Portfolio—Technology Roadmap*. The role of these sources in SNM movement detection, however, remains ill-defined. Development of detection methods now underway will inform future investments in source technology. In recognition of this, the prioritization scheme applied to neutron source investment options (**Table 8**) consisted of estimated impact levels derived from the capability to produce a balanced improvement in neutron source technology as a whole, with some emphasis on directional neutron sources.

Table 8. Prioritized investment options for neutron sources.

Investment Option	Priority	Impact	Summary
Next-generation ion sources	High	High	At the heart of neutron sources is the presence of accelerated ions that produce neutrons via nuclear reactions. Revolutionary advances in ion-source capability may require innovative methods of ion production, for example, by dramatically increasing the efficiency of ion generation, operating for longer lifetimes with greater stability, and optimizing accelerator and target performance. Recent breakthroughs in micro-scale ion sources offer the possibility of revolutionary advances in overall system size, mass, and power consumption. One area of research exploits field desorption wherein micro-electro-mechanical/nanomaterial manufacturing techniques or other approaches are used to populate an anode area with a large number of nanoscale tips. Deuterium and/or tritium ions can be desorbed from the surface of these tips and accelerated toward a high-voltage target [Sch05]. Another potentially advantageous approach creates deuterium ions by heating a pyroelectric crystal in a vacuum. Upon heating, temperature changes cause a migration of positive and negative charges. When outfitted with sharp electrodes, this charge creates fields large enough to ionize and accelerate deuterium [Nar05]. These immature techniques possess potential to increase present neutron source capabilities.
Robust, human-portable systems	High	High	Development of neutron sources with yield in excess of $O(10^9/s)$ that reduce system mass, size, and power consumption by an order of magnitude is an important near-term goal. It is likely for these sources to rely on DD and DT reactions, but switchable radioisotope sources may fill a need in specific applications where system size is the paramount specification and high neutron yield is not required. Component technologies may need to be developed as part of an overall systems development effort, such as advances in high-voltage power supplies to enable a 150-kV system operating up to 100 μA in compact system of size less than 1,000 cm^3.
Directional beams of high-energy neutrons	High	High	Directional beams of high-energy neutrons will be required for standoff interrogation applications. Traditional approaches, for example, rely on lithium ion beams for inverse kinematics using the $p(^7\mathrm{Li},n)^7\mathrm{Be}$ reaction. These approaches must be incorporated into a transportable system with reasonable footprint and operational requirements. Other innovative approaches to directional beams are also of interest.
Transportable, high-flux sources	High	Medium	Some applications require intense neutron yields of $O(10^{11}/s)$, but such sources must be transportable (i.e., capable of being set up and torn down in time scales of days while maintaining reliability). Alternatively, plasma-focus neutron sources are attractive due to their potential of producing very intense and very short neutron pulses. All sources require the development of more efficient and compact high-voltage power supplies, such as those capable of up to 10 mA at 150 kV in a package of $O(10^5\ cm^3)$ for a transportable system.
Scenario definition for standoff applications	High	Medium	Further investigation into the role of neutron sources in standoff detection is required prior to fully directing technology investments. The same considerations apply to interrogation using other particles, such as muons and high-energy protons. It must first be made clear how each of these proposed interrogation techniques address the requirements of standoff detection. All these methodologies should be carefully modeled and benchmarked to experiments. Upon completion, it will then be possible to make a detailed technology recommendation for neutron- and other particle-beam technology development as it applies to standoff detection.
Advances in time-tagged neutron sources	High	Medium	Time-tagged sources present unique capabilities due to the ability to correlate individual interrogation particles with detection events. The associated particle imaging technique is one example that is particularly useful in the characterization of SNM [Bey90] [Hau07]. In this application, there is a need for small, portable DT systems that have tighter beam spots (~1 mm) and higher yield of $O(10^9)$. More generally, time-tagged sources may provide a viable path toward modestly increasing the standoff distance since detectors could be triggered only by events coincident with neutrons incident on the interrogation target, but this needs careful study and modeling.

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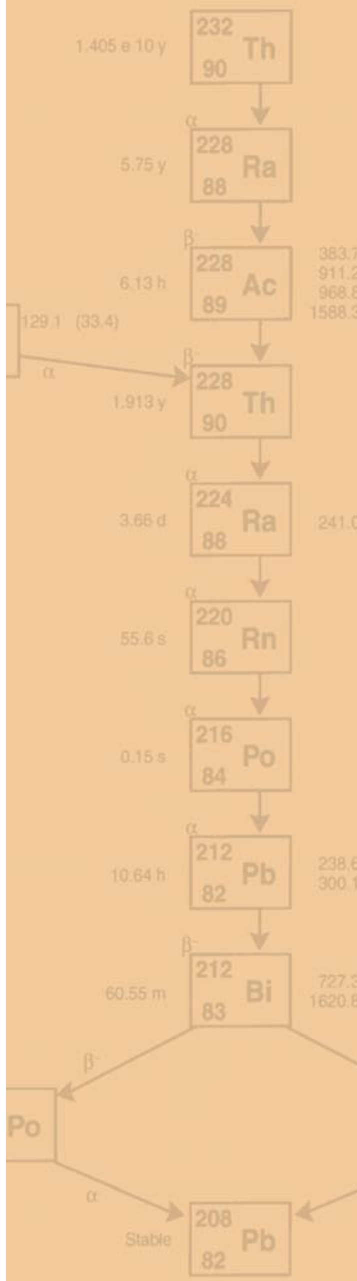

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Office of High Energy Physics Accelerator R&D Task Force Report

Appendix 15

DTRA –
Accelerator Technology for Long-Range Detection of Nuclear Material

Accelerator Technology for Long Range Detection of Nuclear Material

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The Defense Threat Reduction Agency's (DTRA) mission is to safeguard the United States and its allies from global threats due to weapons of mass destruction. This mission requires the capability to detect from a distance nuclear material located in a target object, such as a ship, vehicle or building. One technique being explored to aid the long-range detection of nuclear material is active interrogation using beams of energetic photons, protons, or muons from an appropriate accelerator to stimulate detectable signatures on the target objects. Since the Department of Defense requires a capability to respond to situations anywhere in the world, accelerators used to generate particle beams for active interrogation must be extremely compact and transportable. They must also generate precise beams of sufficient quantity and energy with high efficiency. Photo-interrogation with bremsstrahlung is the most mature technology because an appropriate electron accelerator system can be constructed from off-the-shelf components. Although other beams, such as protons or muons, may be more effective because of low-loss transmission and penetration of shielding or other material surrounding the target, compact and mobile accelerators needed to produce these beams are not presently available. DTRA supports development of accelerators-such as compact, high-current cyclotrons, high-gradient linac cavities, and Fixed Field Alternating Gradient (FFAG) accelerators. DTRA is developing test ranges where accelerator based active-interrogation methods can be studied with relevant test objects. This presentation describes DTRA's unique requirements for accelerator technology and seeks to establish or promote collaboration to leverage other ongoing or planned work. Although DTRA's requirements are unique, spinoff technologies would support non-security applications such as medical therapy and other industrial applications along with fundamental research in developing novel acceleration methods. Advances in accelerator technology may enable applications previously found to be impractical such as accelerator-based actinide disposal, accelerator production of tritium and ^{3}He, or production of technetium-99 from accelerator-generated fission fragments.